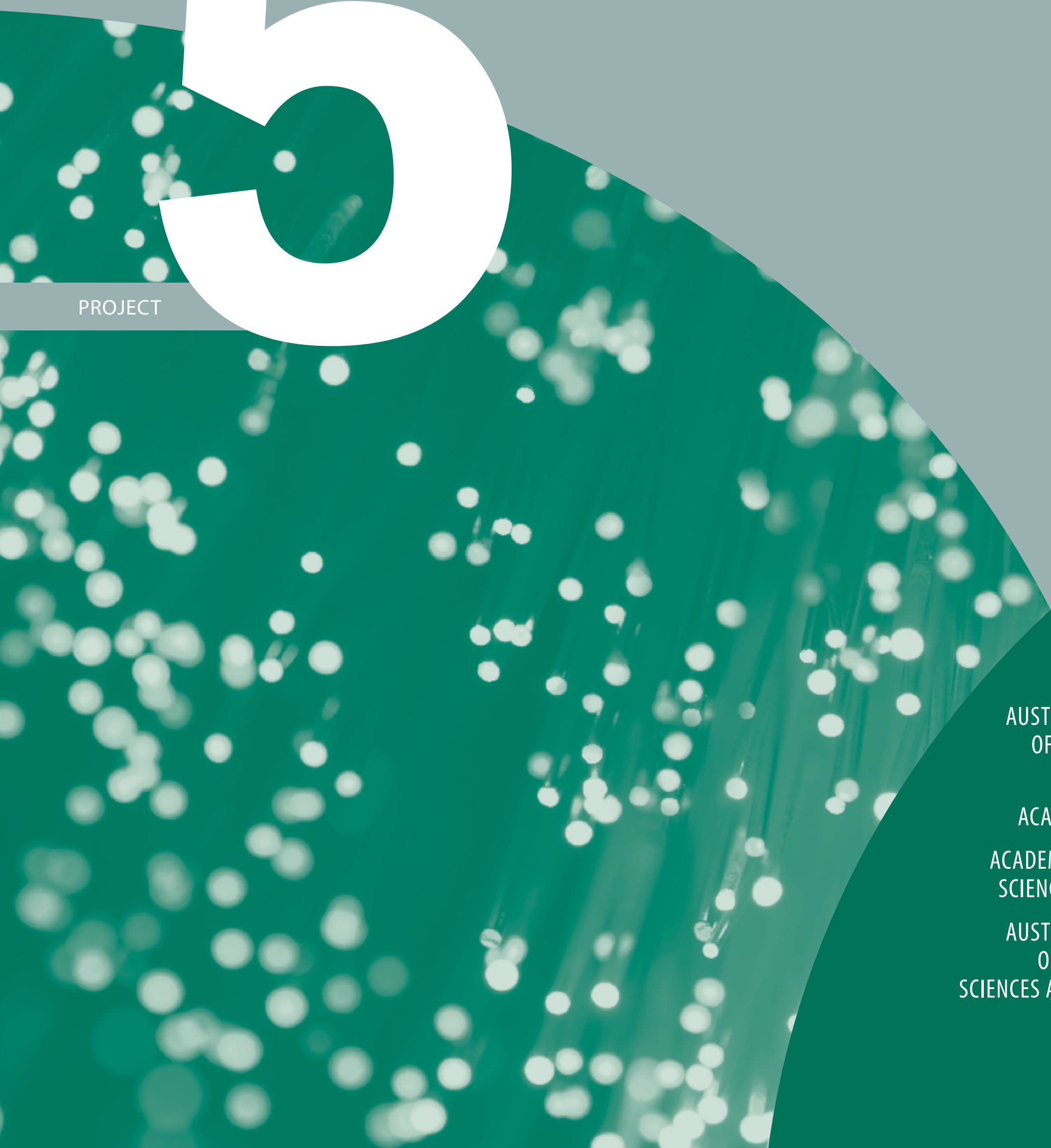
SECURING AUSTRALIA'S FUTURE

Technology and Australia's Future

New technologies and their role in Australia's security, cultural, democratic, social and economic systems

ONLINE HYPERLINKED EDITION

PROJECT 5



AUSTRALIAN ACADEMY OF THE HUMANITIES

AUSTRALIAN ACADEMY OF SCIENCE

ACADEMY OF THE SOCIAL SCIENCES IN AUSTRALIA

AUSTRALIAN ACADEMY OF TECHNOLOGICAL SCIENCES AND ENGINEERING

ACOLA

AUSTRALIAN COUNCIL OF LEARNED ACADEMIES

ISBN 978-0-9943738-0-9

Please attribute and cite the work as:
Robert C. Williamson, Michelle Nic Raghnaill, Kirsty Douglas and Dana Sanchez, *Technology and Australia's future: New technologies and their role in Australia's security, cultural, democratic, social and economic systems,* Australian Council of Learned Academies, September 2015.

This ONLINE version is based on the original file the authors wrote in preparing the report. The printed version of the report, available at www.acola.org.au, was derived from it and only differs in format, the absence of the present paragraph, and the inclusion of some general material about ACOLA and the other SAF projects. The present version is provided because its format makes it easier to read online, and in particular it is internally and externally hyperlinked.

DATE OF PUBLICATION September 2015

PUBLISHER

Australian Council of Learned Academies
1 Bowen Crescent
Melbourne, Victoria 3004, Australia

AUTHORS

This report was written by:

Professor Robert C. Williamson FAA
Dr Michelle Nic Raghnaill
Dr Kirsty Douglas
Ms Dana Sanchez

The report incorporates written input from:

Professor Robin J. Evans FAA, FTSE
Professor Gerard Goggin
Dr Bernadette Hince
Professor Ron Johnston FTSE
Dr Katrina Jungnickel
Dr Michael Keating AC, FASSA
Professor Stephen King FASSA

The report was prepared with input and guidance from the Expert Working Group:

Professor Robin J. Evans FAA, FTSE (Co-Chair)
Professor Robert C. Williamson FAA (Co-Chair)

Dr Genevieve Bell
Professor Roderic Broadhurst
Professor Gerard Goggin
Professor Ron Johnston FTSE
Dr Michael Keating AC, FASSA
Professor Stephen King FASSA
Professor John O'Callaghan FTSE

At last – a narrative for Australia

For many years we have debated where we are heading as a nation. We have been fortunate to have had a relatively prosperous and happy existence and tend to think that this is a direct result of our abundance of minerals and our agricultural production. While our prosperity has been dependent on resources it has only worked because we have been world class in our production techniques and the technology and scientific research that sits behind them. Make no mistake, Australia is not alone in having huge quantities of iron ore: Brazil has just as much and it is generally higher grade. We compete against the world for our economic success.

But what of the future? We seem to have no clear narrative other than that as a small nation we must compete against the rest of the world. And the future can be frightening when one notes the way technology is utterly changing the landscape. Some of the wilder predictions suggest that by 2030, 80% of all jobs will be in firms or institutions that don't exist now. Aviva Rutkin writing in the MIT Technology Journal[1] on the jobs of the future suggested that around half of all currently existing jobs in the USA would be automated by 2030.

The good news of course is that while technology is destroying jobs it is also creating jobs. Our narrative then is clear: we must pursue innovation through technology as the main contributor to our future prosperity and happiness. The new jobs generated will allow us to compete with the world. The demise of our car industry tells us what can happen if we don't take on this challenge.

This report is a narrative for the future because it is technology 'that is central to human existence and is important for Australia, both now and in the future.' One cannot sensibly think about Australia's future without also thinking about Australia's future technology.

A few years ago, the Chief Scientist, Prof Ian Chubb commendably commissioned the learned academies to work together to investigate key challenges facing the country and to identify opportunities. Invoking the four academies covering the humanities, social sciences, science and engineering and technology was a brilliant step as any challenge of significance inevitably spans across the disciplines: technology is no exception as this report explains.

The team generating the report was asked to consider (in my words) what technologies were the most promising for Australia to pursue. Where this report is extraordinary is that, in essence, it has suggested this is not the way to consider technologies for the future. No one has ever been successful in predicting where technology will lead, equally who will be the winners and who the losers. For every new technology there are inevitably winners and losers. What the report does do however is show how one can win in the technology race; how one can focus on changes and impacts and, most importantly, on interventions that help us deal with the unpredictability of technology.

Uncertainty, innovation and risk are all tightly linked and all command or demand intervention. Just because we are uncertain of the future doesn't mean that it is not clear that action is required: but what action? What is most needed is a problem oriented focus where we identify problems, do proper experiments, accept and deal with failure early and move on to try other experiments. Riding on the shoulders of others (shamelessly stealing but preferably with acknowledgement) is far more efficient than waiting till the path is clear. This is where we can look to our own experience that the more practice we get at something, the better we get at it.

---

[1] http://www.technologyreview.com/view/519241/report-suggests-nearly-half-of-us-jobs-are-vulnerable-to-computerization/

Those people and companies and governments that try something new (i.e. innovate) get better and better at interventions and innovation while those that wait will lose out. The principle applies whether it is singing, skiing, sailing or using new technology to innovate, the more one tries, the better one gets.

Interventions can succeed even in the face of the uncertain future. They include improving the focus on adaptability when educating people so when jobs come and go, people are better able to adapt. It seems less than efficient but putting 'tinkering' up there with other laudable educational goals is training for lifelong adaptability. The path from a student tinkering with technology, to an adult being able to adopt, adapt and exapt (use for new purposes) new technologies for good is a compelling one.

There is some brilliant work done recently by the OECD on the specific topic of what drives uptake of low emission technologies in different countries.[2] It deserves wide reading and is fully in line with the findings in this report. So what makes some countries better able to grasp the handle of new technology and innovate? It is not the base level of science and R&D, important and all as that is. Rest assured on this note that we already perform at the level of 'average' in Europe. The OECD goes on to suggest it is the level of innovativeness in a country. This is even more important than direct market incentives such as a mandated level of renewables or a carbon tax.

I would not go so far as to suggest that our sole focus should be on technology, especially if at the expense of science and basic research and development since these are all so deeply intertwined. I would suggest however that given Australia sits at the bottom of the OECD ladder in terms of firms collaborating on innovation with higher education or public research institutions, we have to adopt some novel approaches to energise our capabilities in innovation. The Conclusion chapter in this report is aptly titled 'Adapt or wither'.

This report provides a narrative for the future and a clear path through the jungle of ever changing technology – terrifying in prospect if we get it wrong and exhilarating if we get it right. I'm convinced that wide readership of this report will change the way Australia thinks about technology and its future.

Robin Batterham AO

Fellow of the Australian Academy of Science, Australian Academy of Technological Sciences and Engineering, Royal Academy of Engineering, Swiss Academy of Engineering Sciences, National Academy of Engineering (US) and the Chinese Academy of Engineering.

[2] Haščič, I. et al. (2010), "Climate Policy and Technological Innovation and Transfer: An Overview of Trends and Recent Empirical Results", *OECD Environment Working Papers*, No. 30, OECD Publishing. http://dx.doi.org/10.1787/5km33bnggcd0-en

Project aims

The project (Technology and Australia's Future: New technologies and their role in Australia's security, cultural, democratic, social and economic systems) aimed to understand the role of new technologies in Australia's social, cultural, democratic, security and economic systems. The expert working group and project team were asked to answer the following questions:

Q1. What are the key science and technology developments currently affecting Australia's social, cultural, democratic, security and economic systems?

Q2. To what extent can new developments in science and technology, and their economic and social impact, be anticipated? What are the key factors affecting such anticipation? What are reliable time horizons for prediction and what factors affect that horizon? How should technological uncertainty and risk be assessed and communicated? How should the process of policy development and government policy incorporate technological uncertainty and risk assessment? What are the time scales that government policy needs to operate on in order to effectively influence adoption and use?

Q3. What are the potential impacts of new and emerging technologies on Australia's social, cultural, democratic, security and economic systems?

Q4. What are the key determinants (in Australia now, and in the foreseeable future) of industry's uptake of new technologies and to what extent are these capable of influence by government policy?

Q5. What are the opportunities, barriers and determining factors for new or different uses of modern information and communication technologies (ICT) broadly across Australia's social, cultural, democratic, security and economic systems?

Q6. How should all these questions be considered by Government in an ongoing fashion in the future?

We have given answers to these questions below, but have explored a range of issues in the main report inspired by and going beyond the questions. Our overall aim has been to synthesize current knowledge regarding new technologies, and especially to provide guidance regarding how governments can and should respond.

Summary and Findings

Technology and Australia's Future examines how technology has changed in the past, how it will continue to change in the future and what one can consequently say about the impacts of new technologies on Australia. The report aims to provide government and industry with guidance that will endure over the long term; it does not only look at the technologies of today or those categorised as 'emerging' technologies. *Technology and Australia's Future* focuses on how technology changes, the nature of its impacts, how it can be predicted and the types of interventions that help deal with the complexity and uncertainty inherent in technological change.

Technology is central to human existence and is of great importance to Australia both now and in the future. The history of technology and the history of human development are deeply entwined. Human beings have pursued technological opportunities in all of their activities – food production, comfort and safety, defence, transport, trade and commerce, information, media and communication, art and culture, health, sanitation, reproduction, manufacturing – everything. The study of technology development as an activity independent of the social and economic development of *Homo sapiens* would miss critical aspects of the evolution of technology and the impact it has on being human.

Technological *change* is a major driver of social change and the dominant source of economic growth. It encompasses the processes of invention, innovation and diffusion of technology. While often used, linear models of technological change (e.g. basic research leads to technological development which then leads to product commercialisation and diffusion), are rarely accurate. Technologies change through a complex web of factors with many feedback and feed-forward mechanisms. Interventions intended to enhance technological innovation are likely to be of little benefit if they are based on simplistic models. Technological change is comparable to biological evolution: it is unpredictable in detail, but there are general patterns that recur including path-dependence, multiple invention, punctuated equilibria and recombination of ideas. Technological change can be facilitated by enhancing the interoperability of technologies.

Old technologies continue to have a lasting influence through technological inertia and momentum. Technology changes primarily through parts-assembly whereby existing technological components are combined together in new ways.

It is difficult to determine the impacts of technologies. A technology can cause many impacts and an impact can be caused by many technologies – directly, indirectly, individually or in combination. Impacts can depend upon social, cultural, geographical and historical context. Depending on context, technologies can produce results that are desirable or undesirable, and that change over time**.** Uses that are considered negative or threatening at one time may be considered beneficial at another. This tension is evident in the case of personal and national security, where the appropriate balance of privacy and surveillance remains contested.

Information and Communication Technologies (ICT) are the most general of general purpose technologies, and have very broad impact across Australia's social, cultural, democratic, security and economic systems. ICT platforms are valuable due to their generativity (their ability to enable and induce other changes), and facilitating this generativity can have a large positive effect. Data analytics is especially significant at present and can be expected to have large impacts across all sectors.

Predicting future technologies and their impacts is uncertain. Within certain constraints and sufficiently short timescales, it is possible to predict narrow technological improvements, but one cannot accurately predict the long-term impact of a particular technology. There are however general patterns of change that are likely to recur as technologies develop. Acknowledging these patterns can help decision-makers plan for and adapt to change. Given the strengths and limits of prediction, it is valuable to identify the problems that need to be solved and allow technological innovators to find solutions, rather than attempting to forecast the impact of particular technologies.

Technologies can be understood in multiple ways. A technology is an object (a mobile phone), a component (the transistor in a mobile phone), a process (a production line), a service (electronic banking), a network (telecommunication towers), or all of these. Understanding the different levels of aggregation can help explain how technology changes. New technologies develop and are adapted from existing technological artefacts and processes. People can be unaware of the precursor technologies that create and inform new products and artefacts. The way a product or set of products is described can have implications for the way it is understood, evaluated and regulated.

Technologies mean different things to different people. Meanings, values and attitudes greatly influence the adoption of technologies. Personal experiences affect how technology is perceived, predicted and adopted. The way people think, feel and talk about technology makes a difference to how it is designed, evaluated and used. Therefore, decision-makers, policy developers, and innovators need to be aware of the plurality of beliefs about technology and how these might affect engagement with technology in Australia.

Technological literacy, creativity and skills are necessary in Australia for the successful adaptation, adoption and ongoing support of technologies developed elsewhere. In order for industries and businesses to remain competitive, they need the skills and know-how to adopt new technology as it becomes available and adapt their businesses. In addition, businesses need to have the capacity to adapt new technology to meet specific business needs, and to make adjustments and repairs to that technology as necessary. Australia's education systems must develop high levels of scientific and technological literacy, as well as inculcate creativity and a willingness to tinker, which can facilitate the 'learning by doing' that underpins technological change. This will encourage experimentation, giving people, communities and firms the confidence to innovate and adapt under conditions of change and uncertainty where failures will occur.

Governments have a role to play in technological change. Given the underlying importance of technological progress for Australia's future, governments clearly have an interest in facilitating technological change. Governments are inherently risk averse and find it difficult to deal with the unpredictability of new technologies, the risks of failure and the need for experimentation. Consequently, in most cases governments should avoid the temptation to become directly involved in the development of specific technologies by picking technology winners. One exception is where the economies of scale have led to governments becoming the monopoly provider or purchaser of a technology, such as in electricity, telecommunications or defence. In these few instances governments have to invest in particular technologies, which subsequently may have flow-on effects for other technologies and businesses.

Governments should play a facilitative role in technological change by creating an economy, a culture, and a society where new technology is encouraged through multiple experiments. Governments can:

- Ensure Australia has an educated and skilled population able to embrace and adapt to the opportunities that new technologies provide.
- Invest in a strong research and development base and require research institutions to be more open with the IP they generate.
- Seek solutions that appreciate the inter-relationships between technology and humanity.

- Regulate the effects due to the use of a technology rather than regulate the technology itself. Technologies regulated in terms of the technology itself can stifle technological progress.
- Mitigate any negative social impacts of technology; for example by regulation or by assisting with the transition to alternative employment opportunities.
- Require that technology evaluation is open, transparent and independent. Evaluation of new technologies should take a broad perspective and comparing them to the benefits and costs of existing technologies.
- Facilitate interoperability; technologies, systems and organisations can implement standards that allow the assembly of different parts. This can encourage innovation and help to avoid the negative effects of technological lock-in.
- Implement mechanisms that allow for explicit, efficient and adaptive experiments and trials, which will help deal with uncertainty and unforeseen (and unforeseeable) impacts.

Australia has substantial opportunities to benefit from new and emerging technologies. The way Australians understand technology has profound implications for the development, uptake and use of technologies. This report, *Technology and Australia's Future,* presents effective ways to think about technological change, and how Australia can adapt to it, embrace it, and derive the maximum benefit from it. The detailed findings of the report are outlined below, numbered F1–F18.

Technological change drives economic growth in Australia

Development and diffusion of new technology is the major source of Australia's industrial and economic growth, consumption and productivity. New technology arises from change – change in existing technologies and change in the way technology is created, adapted or used. Improving Australia's ability to direct and adapt to technological change can lead to substantial national benefits.

F1. **Technological change is the major driver of long-term economic growth. In an environment of uncertainty, ongoing investment in the skills and organisational capacities that allow effective technology development, evaluation, adoption and adaptation will help solve social, economic and environmental challenges, leading to a prosperous and healthy future.**

Technology and humanity shape each other

In profound ways, technology and humanity create and shape each other. As we build our tools, so they build us.

Human actions change the form and function of tools, products, and artefacts over time, while technology changes human beings too – their behaviour, habits, ways of thinking, bodies (right down to their cells), throughout their lives and the lives of their descendants. These feedback loops between technology and human evolution and their ramifications for human physiology, behaviour, societies, and environmental impact will continue. People are not distinct from the technologies they are surrounded by and use – they are defined and shaped by them. Understanding the technological past helps navigate the present and future. The study of history of technology and the ways in which technology and societies interact would be valuable additions to every Australian's technological education.

F2. **Technology and humanity shape each other. To solve Australia's social challenges, government policies and programs should understand the interrelationships between technology and humanity – solutions to complex problems will never be solely technological.**

Technology categories are subjective and fluid

Classification simplifies description. A ‘telephone’, a ‘sensor network’, or ‘nanotechnology’, for example, are conceptual shorthand for bundles of complex components. But these categories are often ambiguous, can overlap and change over time. How technologies are grouped or categorised has implications for how they are understood and used. Nanotechnology, for example, simply means technology with a nanoscale component. Big data and metadata are still just data. And energy storage technologies, for example, can range from small electrochemical batteries to large-scale pumped hydro schemes.

Likewise, classifying by sector – such as health technologies or defence technologies – produces categories so broad they are unhelpful for technology prediction and evaluation. Technological development cuts across existing categories, so restricting analysis to those categories can be misleading and limit opportunities.

F3. **The way technology is categorised affects how it is imagined, evaluated, funded, adopted and used. Encouraging crossover between diverse areas and looking beyond narrow categories, sectors, and disciplines for inspiration will increase opportunities for technological innovation in Australia.**

Technological change is complex, interconnected and uncertain

Technology is dynamic, interconnected, and constrained by history, geography, economy and culture. Any given technology is a combination of many components from a variety of sources, within particular historical and cultural settings. Innovation does not follow a set pattern from basic research through to applied research to product development. It emerges from a combination of factors including policy settings, economics, skills, investment, and research and development.

Once a technology becomes widely adopted, it becomes embedded in a web of connections between manufacturers, developers, businesses, industries and users. As the entire system becomes ‘locked in’ to a technological trajectory, it becomes increasingly difficult to effect change, even when change would bring clear benefits. Technological inertia creates challenges including the difficulty of integrating new technology into existing infrastructure designed for different technologies, vested interests amongst business owners who enjoy the rents of current technologies, and resistance to changing workforce skills.

The uncertainty of future technologies is a reflection of the openness and indeterminism of the technological future; Australia has a choice with regard to which technologies it embraces and adopts.

F4. **Public policy is often based on assumptions of stability, predictability, and linear progress. Policies which take into account the dynamic and multidimensional nature of technology will encourage adoption rather than protecting and favouring the status quo, allowing Australians to make better decisions to prepare for, and capture benefit from, technological change. Australia’s technological future is open, and not pre-determined.**

Prediction of future technology and its impacts is fraught with uncertainty

Predictions of future technology seek to reduce uncertainty and surprise. It is difficult to accurately predict future technologies and their impacts. It is particularly difficult to forecast the commercial success of a given technology. The difficulties of prediction arise from the interdependence of different technologies, together with socio-economic and political factors.

One can predict:

- Specific technological improvements over short timescales (e.g. the density of transistors on a microchip);
- That technologies will change in an evolutionary manner – there will be many sources of novelty and selection, and it will be difficult to predict which technologies will survive;
- That technological inertia will persist, delaying new technologies and making it difficult to influence change in an established technological system;
- That general purpose technologies – which are pervasive and have many spillover effects – will continue to have a large impact, but there is enormous uncertainty about exactly what the impact will be, or what the models of adoption will be;
- That, due to the long timescale associated with large-scale technological impact, most of the technologies which will have a substantial impact on Australia in the next decade already exist in some form;
- That some problems will be solved with technology, but it is difficult to predict which technology will be involved, or when those problems will be solved, or what the solution will cost.

Forecasts that recognise the dynamic, interconnected and constrained nature of technological change are more likely to be accurate than those which are based on assumptions of stability, predictability, and linearity in innovation.

F5. **Predicting future technology and its impact with any accuracy is extremely difficult. Recognising that general patterns of technological change will persist can help governments, businesses and communities facilitate and adapt to change. Attention should be focused upon problems that need to be solved and on helping innovators find solutions.**

Technologies for data will transform most industries, and be central in solving societal and technological problems

Existing general-purpose technologies will continue to have a large impact while evolving gradually. For example, energy will continue to be distributed via electricity infrastructure, but the electricity distribution network will transform through the continuing growth of renewables and small-scale generation combined with local energy storage.

Because information, communication and control are central to all human activities, information and communication technologies (ICT) will arguably continue to play the greatest role of existing GPTs. Within ICT, technologies for making sense of data (data analytics) are likely to have the greatest growth and impact.

Data analytics is already transforming every industry, from agriculture to education. This pervasive transformative trend will likely continue.

F6. **Technologies for data, especially data analytics, will play a substantial role in solving most social problems, and will augment and transform most existing technologies. In order to maximise the benefit of this technology, Australia needs to ensure it has the advanced skills and capabilities to create and use this technology.**

The value of a technology is not intrinsic – it is contextual and extrinsic

People sometimes ascribe qualities such as virtue or immorality, disruptiveness, usefulness, sustainability or social equity to technologies. These qualities are extrinsic, meaning they result from the way the technology is used, not the technology itself. That is, any given technology may be effective for one purpose, and poor for another. Even the passage of time can change the value of a technology in a particular context.

Technologies are products of particular historical, cultural, geographical, political and socio-technological contexts. Because of this historical and cultural specificity, a technology may be popular in one place or at one time and not another, and it will have particular impacts in some situations but not in others.

F7. **The value of a technology always depends upon context and use. Judging technologies as intrinsically beneficial or detrimental limits the opportunities to make the best use of them. To improve the design, assessment and effectiveness of technology or any technological intervention, consider the technology in its historical, cultural, geographical, political and social contexts.**

Any given technology will benefit some and disadvantage others

New technologies benefit some and disadvantage others through complex causation, affecting employment, health, wealth, and happiness differently. The potential impacts of any new technology should be analysed at a fine-grained level, not just in aggregate across the population, because aggregates can hide differential impacts. For example, while there is no historical evidence that technological change leads to long-term increases in unemployment, workers faced with a new technology that makes their skills obsolete will rightly recognise they are disadvantaged. A major cost of new technologies is occupational obsolescence. Training workers to be adaptable can diminish this cost.

There are several ways to mitigate differential impacts of technological change:

- Occupational obsolescence can be mitigated by ensuring that vocational training targets tomorrow's jobs rather than yesterday's, and by training people to be adaptable.
- Programs that promote technology literacy for all Australians can make the benefits of new technologies more widely accessible.
- Social safety nets can reduce the prospect of individual harm.

F8. **The adoption of any new technology in Australia will affect people differently. Costs and benefits of a technology should take into account the different impacts a technology will have on different sections of society.**

Meanings associated with technology substantially affect technology adoption and use

Meanings play a substantial role in how technology is imagined, designed, adopted and used. They are ingrained, diverse and dynamic, and need to be considered in any technological intervention. Meanings are related to values and beliefs, personal experience, cultural influences, professional and social practices, and collective identities. Understanding how the use of a technology will affect people in their homes or workplaces will offer insight into their choice of whether to adopt the technology. Any technology can mean different things to different people and any intervention by a company, industry or government will generate a range of responses, many of them unpredictable.

F9. **Meanings associated with technology are deeply tied to values, beliefs, experiences and cultural setting, and as a result vary enormously. The meanings people ascribe to a technology substantially influence its adoption and use, and therefore cannot be ignored in any technological intervention.**

Attitudes towards technology can be complicated and contradictory

There is no simple relationship between attitudes to technology and behaviour in relation to it. Attitudes are complex, and are formed from collective and individual values and beliefs in cultural, social and professional settings. Acknowledging the importance of attitudes and personal experience when it comes to technology can help improve understanding of the choices Australians make on whether to engage with technology. Choosing not to engage with technology can take many forms and the reasons can be complex and nuanced.

As influential as attitudes about technology are, people's behaviour with technology can be at odds with their fears and concerns, and attitudes are not fixed. For instance, the highly public debate about online privacy and security does not discourage most Australians from using the internet. Many people who express concern about online 'invasions' of privacy often fail to take basic precautions (the choice of strong passwords, for example) to ensure their online security.

F10. **Attitudes towards technology do not always reflect behaviour. Effective government policy to encourage new technologies should reflect the different reasons people have for engaging with technology.**

Creativity and skill underpin technological change

An innovative society fosters the appropriate knowledge and skills to imagine, design, engineer, manufacture, diffuse, adapt, choose and use technologies. New technology is not merely the product of professional technologists or technology companies. Technology creation and use requires multiple actors: designers, makers, users, scientists, researchers, marketers, policymakers and enablers. These roles can overlap and change over time. Underpinning all these specific skills is the capacity to adapt. The effective development and use of new technologies requires all of these skills. The benefits of importing leading-edge technologies into Australia will not be realised unless Australia has the people to develop and use the technologies. Australia's ability to choose, use and adapt leading-edge technologies requires a high degree of technological literacy.

Workers who are provided with general problem-solving skills, trained to embrace change and think creatively, and who can experiment and 'learn by doing' (hands-on practical experience with a technology) will be in a strong position to help Australian businesses adopt and adapt new technologies. Technology is more than a means to address utilitarian needs – it is a vehicle for creative expression. Encouraging hands-on tinkering with technology can instil a creative perception of technology that can lead to better engagement. Positioning technology as a vehicle for human creativity can inspire Australians to create, adopt and modify technology.

Technological literacy is central to individuals and organisations making appropriate decisions about new technologies.

F11. **Adaptability and creativity are key skills in creating, assimilating and adopting new technology. The adoption of new technology and its effective use depends on people with diverse skills playing a variety of roles. Enhancing technological literacy, including fostering skills appropriate to engaging with technology in all levels of education, can enhance Australia's ability to adopt and adapt new technologies. Promoting technology as a creative enterprise may serve to inspire a greater engagement with technology. Enhancing the tinkering aspect of STEM education at all levels (K-12, and tertiary) could create a culture that embraces technological change.**

Technology evaluation underpins technology adoption

Technology evaluation (determining the costs and benefits of a technology) is complex, contested, and context-dependent. The way in which a new technology is evaluated affects investment in it, its adoption by users or industry, people's attitudes towards it, and its long-term impacts. Ongoing technology evaluation aids decision-making by comparing the costs and benefits associated with various technologies, allowing the anticipation of beneficial or detrimental impacts of technology. It also allows comparison between technologies.

Evaluation is enhanced if data is available, reusable and sharable. Open and transparent data improves technology costing and analysis, allows open critique of evaluation and provides a greater degree of trust in technology choices, interventions, and decisions. The credibility of assessment methods depends on transparency and on avoidance of vested interest.

F12. **Technology evaluation is of central importance to technology adoption. The costs of a technology are complex to determine, context-dependent, variable, and contested. Governments can facilitate better technology evaluation by adopting international best practice and by minimising the role vested interests play in technology evaluation.**

Technology evaluation, analysis and prediction are influenced by cognitive biases

Cognitive biases are pervasive. They influence how people seek and process information. In the context of new technologies, they have substantial impact on how risk is assessed and how technology is evaluated, both formally and informally.

Some undesirable consequences of cognitive biases in technology evaluation can be mitigated. Optimism bias, which is a major factor in the inaccuracy of estimating the costs of a technological project, can be mitigated by reference-class forecasting, whereby empirical data for analogous projects is incorporated into the analysis.

F13. **Cognitive biases play a major role in the evaluation of technologies, which in turn is a major determinant of adoption and use. The impacts of these biases can be substantially mitigated by adopting methods designed to counter them, including independent assessors, and readily available empirical data.**

Continuing government investment in technological research and development is vital to Australia's ability to adopt, adapt and develop new technologies

New technologies are substantially underpinned by fundamental research and development. The economic returns to such research are often slow to be realised and difficult to appropriate for several reasons, including complex interdependencies between technologies. Consequently, governments around the world continue to invest in early stage technology research and development. Increased investment leads to substantial long-term national profit – a wise business decision when Australia is faced with decreased revenue from some traditional sources. In addition, there is considerable support for the promotion of strong national innovation systems, capable of absorbing and transforming the knowledge outputs of basic research. Research institutions that do not attempt to appropriate the returns to themselves generate larger long-term economic returns to the region and country in which they sit.

Government R&D support is best focussed upon general purpose technologies for several reasons: their impacts take a long time (precisely why state support is needed); they have a generality of impact (so the impacts will likely be large) and because of the high level of aggregation inherent in their definition, one does not 'pick a (narrow) technology winner' which can be problematic because as technologies evolve, what is the winner today, or in a given context, may be the loser tomorrow or in a different context.

F14. **The difficulty of appropriating economic returns from early stage technology research and development means that substantial ongoing government investment in research is warranted. Increased investment in high quality scientific and technological research will lead to greater commercial and economic outcomes for Australia. Such research should be focussed upon general purpose technologies, rather than particular technology winners. Having research institutions that are more willing to share their IP will create a more effective innovation system.**

Technology is best regulated via its effects

Technologies emerge into existing regulatory environments. Often existing regulatory systems are sufficient to deal with the impacts of new or emerging technologies, particularly when specific effects due to the use of technology are regulated.

In some cases existing laws and regulations can be adapted to new technology with relative ease. For example, autonomous vehicles can be adopted within existing legal frameworks that regulate the liability of manufacturers, retailers and consumers. In other cases, new technology puts pressure on existing laws and regulations and may need to be redesigned to deal with new uses of technology.

F15. **Government policy and legislation should focus on the effects due to the use of new technology, or the effects arising from new uses of technology, rather than on the technology itself in order to minimise regulatory impediments.**

Interoperability of technologies is central to their design, development and adoption

Technologies are assembled from existing components or parts, potentially drawn from anywhere in the world, combined in new ways (parts assembly). New technologies that cannot operate with existing technologies are less likely to be adopted. Diffusion of technology is facilitated by the ability of parts to work together (interoperability) and the implementation of simple standards to facilitate parts assembly. The ability to make technologies, systems and organisations function together is fundamental to directing and responding to technological change. Interoperability is not merely a technical problem; social and organisational factors matter too. But technical interoperability is important and can be facilitated by modularity, platforms and standards.

- Modularity also aids the development of market structures – having a wide range of interoperable components offers many business opportunities.
- Standards can speed technological change (by enhancing interoperability), but they can also slow it, by locking-in old technologies. Having multiple lightweight standards that themselves interoperate via gateway technologies is a possible way of avoiding premature lock-in. Standards also facilitate trade and hence the adoption of global standards can aid the integration into global supply chains.
- A technology platform allows others to build products and services upon it. Platforms are therefore a natural focus for standardisation.
- Governments can encourage standardisation, but industry is typically best placed to formulate technological standards.

F16. **Interoperability allows the more rapid adoption of new technologies. Interoperability is facilitated by standards and gateway and platform technologies. Diffusion of technology in Australia can be aided by simple standards which lead to easier parts assembly. Adopting global standards will facilitate integration of a technology into global supply-chains.**

Experimentation and adaptability can deal with the failure and uncertainty associated with new technologies

Technology changes through an evolutionary process involving history, environment, persistence, accident and failure. Commercial success and social acceptance of technologies result from learning by doing and serendipity. All technology is developed and improved by trial and error. Uncertainty and failure must be accepted as an integral part of the process of technology development if Australian businesses and communities are to persevere and flourish under conditions of technological change.

Technologies are imperfect, especially when first introduced. The ridicule, stigma, punishment, and penalties associated with failure or the fear of failure hinder innovation and encourage a risk-averse climate. Businesses fail – the entry, exit, transformation and failure of firms is a normal part of economic progress. Large-scale government programs fail. What matters is how this failure is dealt with. By recognising the pervasiveness of failure and adopting best-practice for dealing with it, individuals, businesses and governments can better adapt to technological change.

F17. **Accepting that failure can occur in any attempt to do something new and removing its stigma will facilitate and accelerate technology development and adoption. Training managers in business and government to acknowledge uncertainty, take risks, and deal constructively with failure will improve Australia's entrepreneurial and innovative culture.**

The scientific method is the best way to make decisions about technology

The scientific method provides a useful and transferrable guide to dealing with uncertainty and failure in technology development and adoption. It entails systematic designed experimentation, careful measurement, a focus upon problems rather than methods, a plurality of techniques, an unambiguous declaration of a desired outcome in advance in a falsifiable manner, and transparent peer-review. All of these points, and its core – the adaptive response to failure – can be applied usefully to manage the process of technology development and adoption. Such a scientifically grounded approach:

- Recognises failure as an integral part of technological change, and facilitates learning from mistakes and the more rapid move onto the next experiment (fail, iterate, adapt);
- Focuses attention on the design of valuable experiments;
- Promotes rigorous ongoing evaluation and lifecycle assessment;
- Encourages multiple solutions so that the best option can emerge (rather than picking a 'winner' and forcing it to work);
- Allows different approaches depending on context – there is no one-size-fits-all solution, even within one industry or social group;
- Promotes open and transparent data-sharing that can improve the evaluation of technology;
- Encourages training and skills to facilitate adaptability, resilience in the presence of failures, and the enthusiasm to try multiple options systematically.

F18. **The uncertainty and unpredictability inherent in the development and adoption of technology require a considered experimental approach. The adoption of the scientific method of 'test-learn-adapt' can improve Australia's ability to develop, adapt and embrace new technologies.**

Answers to project questions

The Chief Scientist for Australia and the former Prime Minister's Science, Engineering and Innovation Council asked the *Technology and Australia's Future* project to examine the implications of new technologies for Australia's social, cultural, democratic, security and economic systems.

These systems (described in Section 1.3) broadly involve:

- Australia's interrelated public and private institutions
- Australia's federalism, systems of governance and democratic traditions, network of local, state and Federal laws and regulations, and the agencies and organisations that secure and uphold them
- The services and organisations, governmental and otherwise, that constitute and reinforce Australia' s social welfare safety net
- The formal and informal networks and customs of Australia's citizens, cultural institutions and the material cultures and customs they create, celebrate and preserve
- The systems of production, exchange, finance and capital that support Australia's national economy.

Australia's social, cultural, democratic, security, and economic systems have elements that are characteristic of Australia, but not necessarily unique. Australia is a small market, albeit one in which large multinationals are given to experiment. The technology trends which will influence Australian consumers and manufacturers are global. Opportunities or solutions to problems will not necessarily be Australia-specific, but will be found globally.

The following section answers the six project questions, but is not a summary of the report.

Q1. What are the key science and technology developments currently affecting Australia?

Key science and technology developments affecting Australia are comparable to those affecting other OECD economies. Although Australia has particular characteristics and conditions, many of these features are shared by other countries and regions and the people who live there. Most of the technological challenges of Australia are common to other countries with some combination of isolation, low population densities, limited arable land, long borders, high urbanisation, and a reliance on natural resources. The problems, aspirations, experiences and opportunities of Australians are common to people and organisations in other countries.

Many of the technologies and techniques that affect Australia now (e.g. textiles, concrete, metallurgy, engineering, agriculture, communication technologies, electrification, and automobiles) are centuries or millennia old. The timetable for dramatic technological change is often many decades. People often become aware of a product or process decades after the development of an effective prototype (for example, digital cameras, mobile telephones, electric cars, 3D printers). Because of this typically long time frame, most of the technologies that will have a substantial impact on Australia in the next decade already exist and can be identified at a general level. At a high enough level of aggregation, it is possible to predict general trends in technology. However it is difficult to predict particular impacts and pathways to adoption for specific technologies or products (Section 3.5).

General purpose technologies are widely used across the economy, with many different uses and spillover effects, and with the ability to augment or complement existing or emergent technologies (Section 3.5.2, Box 12). Established general purpose technologies which will continue to have a very significant social and economic impact – with potential cultural, democratic and security implications – include ICT, biotechnology, advanced materials and fabrication, technologies for transport, sensors, and energy technologies. Emerging general purpose technologies (which will spin out from existing general purpose technologies) will have large impacts but there is uncertainty regarding exactly what those impacts will be or what the models of adoption will be. Machine learning, a kind of ICT, is emerging as a general purpose technology with a wide range of applications, significant externalities and growing pervasiveness across the economy.

The report has produced two lists of key science and technology developments that are currently affecting Australia and are likely to continue do so in the near future. The first list collects six general purpose technologies likely to underpin and enable future technology developments. The second list includes technology combinations and systems that are already under way or are highly likely to happen, underscoring the recombinant nature of technology design and innovation. For a description of how these lists were compiled, refer to [343].

General purpose technologies

The following existing and emerging components of general purpose technologies are developing in a direction that can be predicted, up to a point, in the short term. This means that their likely capabilities within 10–20 years can be determined with some degree of confidence.

Information and communications technology (ICT)

ICT is the one of the most general purpose technologies of the present day – it can be applied to solve problems in almost any domain. For example, data analytics is a critical component of many advances in biotechnology. Modelling and simulation underpins the design of advanced materials, new forms of transport and energy production and advances in medical technology. Some emerging and future developments in ICT include increased capabilities in computer power and memory, cognitive computing, networking, humanoid robotics and natural user interfaces. Perhaps the largest impact will be the pervasive use of data analytics across all industry sectors.

Advanced material manufacturing

Advanced material manufacturing involves the use of technology to improve products and/or processes. 3D printing enables increasingly fast, highly capable, low cost and widespread manufacture of goods. Powerful 3D printing systems are capable of printing a huge range of products and devices that are currently manufactured by complex processes. 3D printers are already employed to manufacture advanced components such as turbine blades and aerospace components, orthopaedic replacement parts, and a range of electronic components, see Appendix C.1 [541].

Transport

There are an increasing number of autonomous features and vehicles available to consumers and industry including driverless cars, unpiloted aerial vehicles and electric vehicles. Autonomous vehicles can offer low cost, safe and an efficient means of transport, see Appendix C.3 [931].

Biotechnology

Biotechnology is used to provide solutions to diseases, climate change, fuel alternatives, food security as well as improving quality of life. The near instantaneous and low cost DNA sequencing techniques available is making an impact on the speed and volume of genetic data available. However, the cost to analyse and store vast amounts of DNA data will be significant.

Energy

Improved large and small-scale alternative energy technology, better storage, wireless transfer for low power levels, energy-scavenging technology for many consumer and monitoring applications, advanced power grid control and micro-grid technology (smart-grid), see Appendix C.2 [930].

New primary energy generation technologies (with substantially less overall carbon pollution) and more efficient use of existing gas, oil, coal will become increasingly important.

Sensors and monitoring

Smaller, cheaper, more capable sensing and monitoring technology including new nanotechnology-based sensor systems such as low cost, chip-based biochemical analysis will find application in many areas.

Technology combinations and systems

It is particularly difficult to predict the diverse impacts of technology combinations and systems. While considerable uncertainty exists as to what will be adopted, there are clear trends and commercial opportunities over a 10–20 year horizon. Many of these are already visible in the research literature, patents, new start-up companies and early phase products. The list below suggests some areas where combinations will lead to significant social and economic impact within the next 10–20 years in Australia:

- Computing power + analytics + networking ⇒ automation of analytic work
- Computing power + robotics ⇒ automation of manual work
- Vehicles with autonomous features + sensing + networks ⇒ safe, efficient transport
- Renewable energy sources + sensing + networking + analytics + distributed energy sources => renewable power (smart grid)
- Fast DNA sequencing + analytics ⇒ personalised medicine
- Pervasive sensing + analytics + networks + autonomous vehicles ⇒ safe, sustainable smart cities along with wide scale surveillance of human activities, precision agriculture, smart water resource management, disaster management, mapping of resources
- Nanotechnology + analytics + radiofrequency identification ⇒ automatic food quality monitoring, body function monitoring
- Modelling and simulation + low cost, high-performance computing ⇒ real-time decision-making [305].

The major effects of current technologies can be seen through the industry-transforming impacts of general purpose technologies such as ICT. The greatest impacts emerge at the intersection of different technologies, resulting in new combinations, and their adaptation for new uses (Section 2.2). These impacts will be seen, over a long period of time, in the radical transformation of industries, the closure of businesses, and the creation and growth of new businesses enabled by new technologies.

Q2. To what extent can new developments in science and technology, and their economic and social impact, be anticipated?

The degree to which new developments in science and technology can be anticipated is highly dependent upon assumptions about the past, present and future (Chapter 3). Technology is path dependent – it builds on and is built from what has come before – but it is also subject to market conditions and wider environmental effects. The further into the future a prediction seeks to report, the greater the number of confounding factors. Forecasts based on assumptions of stability, predictability, and linear progress are unlikely to be as accurate as those that recognise the dynamic, interconnected and constrained nature of technological development (Sections 2.2, 3.4)

There are many approaches to predicting future technologies and their impacts (Section 3.3). Some of the key methods include analysis of evidence in patent databases to determine likely directions of technology development; seeking expert opinion from a broad range of technology and industry leaders; analysis of business and investment opportunities; and exploration of user desires, including those presented in science fiction. The time horizon of prediction differs depending on what is being predicted and the motivation (e.g. inspiration, investment, strategic planning or risk management) in predicting.

One can predict:

- Specific short-term technical improvements (Section 3.5.1);
- Specific numerical performance indicators, for example, Moore's Law, which describes the doubling of the numbers of transistors on integrated circuits every 12-18 months (Section 3.3.7);
- That features of technology development will recur – for example, technology will continue to change with constraints, technological inertia will persist, and observation of significant impacts will lag behind their first appearance (Section 3.5.3);
- That future technologies (with associated economic and social impacts) will develop from present technologies (Sections 2.2, 3.4.1);
- That there will be long-term impact from broad classes of technologies. General purpose technologies like ICT, for example, will continue to have pervasive and substantial economic and social impacts in Australia and the world (Section 3.5.2, Box 12);
- That many current technologies will become components of general purpose technologies (Section 3.5.2);
- That technology will form part of the solution for future problems and needs (Section 3.6.2).

However, one cannot predict with any accuracy the long-term social impact of particular technologies. Apart from the impossibility of predicting future scientific and technological knowledge, the impact of technologies is critically influenced by the economics of the technology; thus to predict impact requires a precise and accurate prediction of the economy.

A practical approach to foresighting for individuals, organisations and governments would:

- Focus on a particular problem (which could be a social issue, a security threat, an economic puzzle), and map potential or hypothetical ways to solve it, rather than attempt to forecast a technology and its impact (Section 3.6.2).
- Investigate which of these problems may be amenable to scientific or technical solutions. There are always a multitude of potential solutions to any problem, and a particular invention may hold the key to solving many different problems. Consider several options rather than trying to force a particular technological solution (Section 7.6).
- Invest in open and transparent data to improve evaluation of technology choices, whether retrodictive, ongoing, or predictive. The default should be toward making data more sharable and valuable rather than locking it away, particularly data which governments own, or for which they have custody (Section 7.2).
- Recognise and plan for uncertainty to improve the response to it. Encourage experimentation and a flexible, adaptable attitude to risk and uncertainty, which are inherent in technology change (Section 7.2, 7.4, 7.5, 7.6).

Q3. What are the potential impacts of new and emerging technologies on Australia's economic, security, social, cultural, and democratic systems?

It is difficult to anticipate, define or measure the impacts of technology accurately and reliably (Chapters 3, 4, 0). Any technology choice will benefit some people, usually at the expense of others, and any technology will have desirable and undesirable effects (Appendix 1: Understanding impacts). It can be some time after the widespread adoption of a product, process or system that many of its impacts are observable (Chapter 4).

The consequences of adopting a technology will be shaped by the complex interplay between the supply of new technology, the demand for new applications, and the underlying socio-technical systems within which all new products emerge. The impacts of any technology are shaped by its history and the history of its uses (path dependence), its current uses, and by other contemporary technologies (interdependence) (Sections 2.2, 4.1). Other factors which determine impacts include the level of uptake and adoption of various contemporaneous newly developed technology platforms and user applications. Much of the surprise of technology impact arises from the unexpected ways in which technologies interact and become adopted. In other words, impacts are 'overdetermined' (there is more than one possible reason for their occurrence), which makes it difficult to tease out cause and effect. Almost any technology change of any magnitude will have unexpected consequences. Some of them will be broadly desirable in a given context, some will be considered detrimental. These impacts may be direct or indirect, immediate or yet to occur. Some impacts may have been anticipated, but may still be unintended (Chapter 4, Appendix 1: Understanding impacts).

Society, culture and humanity

(see Section 4.3.3)

Throughout their lives and the lives of their descendants, human actions and decisions over time adapt and change the form and function of tools, products, and artefacts. Technology changes human beings as well; their behaviour, habits, ways of thinking, bodies, right down to their cells. The feedback loops between technology and human evolution, and their ramifications for human physiology, behaviour, and environmental impact continue into the present.

The meaning of technology and related practices play an essential role in human responses to technology change (Sections 5.1, 5.3). The creation and use of technology has led to cultural and social change. Sometimes it is tempting to blame a particular technology for apparent changes or events. Changes in communication practice are often accompanied by widespread anxieties. The rise of electronic social media has been linked to changes in the way people interact with each other leading to a decline in social capital, although this claim is contentious; similar claims were made of the railroad in the nineteenth century. As with any widespread change in the way people communicate and interact, the pervasive use of electronic social media has been accompanied by a significant shift in the ways and the places that people perform social relationships. *Homo sapiens* is a social species, so any fundamental change to the way people socialise implies a change in the way people are human. Any effective intervention would need to consider whether these anxieties are themselves new, and whether they are justified with regard to ICT and in particular electronic social networking, before contemplating what can be done to mitigate any harm to civil and social wellbeing.

Technology has also changed the organisation of work and workplace cultures (Sections 5.1.2,4.3.5). The use of technology to improve business analytics in particular has led to a dramatic increase in the proportion of workers whose main capital is knowledge. This in turn has led to a change in management-employee relations as employers negotiate different management styles to get the best out of knowledge workers. Equally the introduction of different ICT, such as email, into the workplace can change work practices, cultural norms (through the internet office workers can work while not in the office) and practices (interoperability and security issues arise with 'bring your own device'). Recognising the interrelationships between humanity and technology leads to the possibility for a much richer set of interventions on social problems (Sections 1.1, 2.2, 7.2).

Governance and democracy

(see Section 4.3.4)

Because they are designed, made, and used by people, technologies often affect and reflect conditions of power, authority, freedom and social justice. The potential impacts of any technology depend upon how it is used.

Technologies such as television, radio, newspapers and the internet have changed the nature of politics and government by changing citizen interaction with government and with fellow citizens. In particular, the advent of television and the development of the 24/7 news-cycle, with demands for immediate responses to events as they unfold, may have contributed to a more presidential system of government. More recently the internet has enabled devolved political interaction, with potentially more critical and engaged citizens and consequences for Australia's system of governance. The internet has increased the reach and power of individual voices and niche political views. For example, social media has also been used to organise, communicate, and raise political awareness (e.g. during the Arab Spring), but it is also used to the advantage of political parties and advocacy groups by targeting information to the voting public. Simple 'I Voted' messages on social media can significantly increase participation in the democratic process, as was seen with the Obama presidential election. The capacity for technology to influence governance cuts both ways. For example, online petitions may cause elected officials to give attention to issues that receive a lot of online or media support, at the expense of a more inclusive and strategic approach to governance and policymaking.

Technology (as information and data tools) has also allowed better evidence-based policy and the development of services that are more responsive to the needs of individual citizens. Information and the analysis of data are crucial for effective evaluation, which informs policy and program design. For instance, the use of modern diagnostic equipment and data analytics in the health sector allows provision of customised health services that may be much better targeted at the specific needs of individual patients. The quality of the data used, its analysis and how it is translated into policy are essential to the quality of any evidence-based policy.

Economy

(see Section 4.3.5)

Change in technology is the major source of industrial and economic growth and change, consumption and productivity, and the uneven distribution of benefits over time which reflects differences in the rates of adoption and adaptation to new technologies between different countries and regions. To receive the economic benefits of technological change and innovation, Australian businesses and industries will need to be aware of developments elsewhere in Australia and the rest of the world. They will also need to recognise that technological innovation occurs by a process of invasion or colonisation (the flow of ideas, products, components and processes from one sector, industry or firm to another), and that new technologies are created by assimilating parts from other products and technologies (parts assembly).

The economic returns of fundamental research and new technologies and products are rarely appropriated by the inventors. Government investment in early stage technical development including basic research is critical to ensure that Australian industries and businesses benefit from technological change.

Modern general purpose technologies like ICT, biotechnology, and advanced materials and fabrication technologies will continue to have a very substantial impact on Australian society, culture, democracy, security and the economy. Emerging general purpose products (for example, machine learning and robotics) are likely to have a significant economic impact, but there is enormous uncertainty about exactly what that impact will be, or what the models of adoption will be.

Although there has been significant growth in labour supply in most developed countries in the last century, there is no evidence that technological change leads to long-term increases in unemployment. Short-term policies to deal with differential impacts will therefore not be effective if they seek to impede the adoption of new technology. Productive approaches focus on transfer of skills and on re-skilling to enable those whose livelihoods are harmed by the introduction of new technology to adapt to the change, hence the importance of social welfare safety nets. It is important to weigh up the social as well as economic good of any technological intervention.

Security

(see Section 4.3.6)

All technology can be used either to strengthen or weaken security. Almost all technology has security implications of some kind. Early technologies such as fire, stone axes, and spears had the capacity to improve the safety and comfort of human beings, but at the same time served as weapons capable of injuring people and destroying property. The advantage lay with those with better tools. Technologies which provide considerable advantage in the form of energy security – for example, the use of fire, electrification, and fossil fuel technologies – are not always controllable, and when uncontrolled, can threaten human security.

Fire helped to shape humanity. The ability to cook food contributed to changes in human physiology, intellect and gut flora. A hearth provided warmth and protection from predators, encouraging new forms of sociality. Fire has been used to shape landscapes, but when out of control it destroys lives and property. Electricity infrastructure has transformed economies around the world, but if poorly maintained, can start fires, cause electrocution, and fail at critical times. It is powered by energy sources which come with their own baggage. While coal helped fuel an Industrial Revolution, the fuel was a scourge of the working classes well into the 20th century, due to appalling mine accidents, the negative medium to long term health effects for miners, and the sometimes catastrophic effects of domestic coal burning. Coal mines and coal-fired power stations continue to harm people, directly and indirectly, due to accidents, pollution, and the contribution of coal-burning to climate change, but coal and other fossil fuels also provide material wealth and security to millions of people.

In contrast, the threats to security that gain much press coverage, such as terrorism, have actually done *relatively* (i.e relative to other man-made causes of death) little harm (see Fact 27 in Section 4.3.6 for sources for this assertion). But such harm is dwarfed by the potential risks due to cyber-attacks, which in turn are dwarfed by those of unmitigated climate change. This last point shows that segmenting technological impacts into security-related and not security related is not helpful. *All* technologies can potentially negatively impact our way of life. Focussing attention on those with the largest potential negative impacts is indeed warranted, regardless of whether they come with a 'security' label.

Q4. What are the key determinants (in Australia now, and in the foreseeable future) of business and industry uptake of new technologies, and to what extent are these capable of influence by government policy?

Given the variety of factors involved, the diversity of technologies, and the diversity of motivations, requirements, resources, organisational structures and cultures within businesses, there are no universal prescriptions. The uptake of new technologies by business and industry is highly context-dependent. The 12 factors listed below are all important to the uptake of new technologies.

Costs and benefits

A major determinant of technology adoption is the associated costs and benefits. Analysis of costs and benefits is usually not a simple matter, and there are considerable uncertainties, especially when predicting future costs or benefits (Section 3.4.1 and Chapter 6).

Governments can influence costs, benefits and uncertainties by:

- Consistently signalling that technological change is indeed the main driver of economic growth in order to encourage more businesses to embrace new technologies, thus reducing prices.
- Modelling best practice in doing cost–benefit analyses for new technologies. Effective evaluation includes embracing transparency and openness, and minimising cognitive biases (e.g. by using reference class forecasting to increase evaluation accuracy).
- Removing tariff barriers and differential pricing to drive prices down.
- Reducing compliance burdens of regulation to reduce costs.
- Implementing programs for capital de-risking. The US Small Business Innovation Research program, for example, encourages domestic small businesses to engage in government-supported R&D that has the potential for commercialisation.
- Setting national challenges which will inspire technological development and adoption (such as the American space program). Ambitious targets to reduce carbon pollution, for example, can enhance innovative industries and create new job opportunities.

Policies, regulations and laws

Businesses are influenced by government policies, regulations and laws. If these are designed in ways that favour existing technologies over new ones, then businesses will have less incentive to invest in new technologies (Section 7.2)

Governments can influence approaches to policies, regulations and laws by:

- Focusing on the desired goal, rather than the (technological) means – government policies and solutions should avoid endorsing particular technology or infrastructure choices. For example, rather than setting policy for specific technologies – such as carbon capture – policy should encourage decreasing carbon emissions, allowing innovative solutions to emerge (Section 3.6.2).
- Investing in understanding new technologies and exploring their possible range of applications and consequences (Section 6.4).
- Providing policy stability, for example, changing carbon pollution policy discourages long-term investment.
- Assessing the potential costs and benefits of technology using lifecycle assessment (Chapter 6).
- Recognising that most problems to do with new uses of technology can be addressed by common law and do not require technology-specific laws (Section 7.8).

Technological inertia

Technological inertia refers to resistance to technology change, whether deliberate or systemic (Section 2.7). There are several causes of technological inertia which can delay or discourage industry adoption of new technologies:

- Vested interests (expressed through political influence and rent-seeking) can reduce the incentive of a business to invest in new technologies – if incumbents are afforded political protection, then it is not a good investment decision to embrace technologies which are contrary to the status quo (Section 6.4.1).
- Within a business, management and workers can resist technological change if there are concerns they will be worse off under a new regime (Sections 5.1.2, 7.5).
- A business can resist adopting technology because of concerns that the technology will damage its existing business model – the 'innovator's dilemma' (Section 7.9.3).

Governments can influence technological inertia by:

- Limiting the political influence of businesses heavily vested in current technologies, and ensuring that new players have an equivalent voice.

- Publicly recognising that technological change can lead to new businesses that create jobs.
- Directly investing in basic research to encourage technology development and adoption.

Skills

The benefits of importing leading-edge technologies into Australia will not be realised unless Australia has the people to develop and use the technologies effectively. Workers who are provided with general problem-solving skills and trained to experiment and 'learn by doing' (hands-on practical experience with a technology) will be in a strong position to help Australian businesses adopt and adapt new technologies (Section 2.9.3, Chapter 7).

- The workforce, including management, is often trained in particular ways of doing things for a set of contemporary technologies and processes, rather than acquiring general problem-solving skills (Sections 2.9.3, 7.4).
- Lack of worker mobility can slow the spread of skills that allow businesses to exploit new technologies.
- Occupational obsolescence can be mitigated by ensuring that vocational training targets tomorrow's jobs rather than yesterday's. The development of trainees' adaptive capacity may require a shift in vocational training from its present focus on highly job-specific competencies in favour of vocational streams which group a number of closely related occupations.
- Different technologies sometimes necessitate different business models or organisational structures. The inability to cope with organisational change that results from adoption of new technologies will limit a business's capacity to adopt some new technologies (Sections 2.9.2, 5.1.2).

Governments can influence skills by:

- Influencing training and education schemes to encourage flexibility, creativity and the ability to try new things, including encouraging an increased focus on technology and engineering to complement science and mathematics training.
- Minimising constraints on worker mobility.
- Supporting the skill-development role of R&D institutions and recognising that mobility of highly trained technologists is crucial to industry adoption.
- Supporting management of education and training opportunities for Australian businesses by ensuring the training content is sufficiently generic to enable workers to adapt to the evolving job requirements imposed by new technologies, rather than highly specific content that is focused on the old technologies employed in past jobs.
- Ensuring that skills-accreditation organisations do not become change-averse gatekeepers.

Openness

Operating new technologies requires new knowledge and information (Sections 6.4.1, 7.2, 7.9). Businesses can be restricted in their ability to adopt new technologies through lack of access to published research or relevant data. They can also be restricted by strong patent provisions, poor standards, constrained or segmented supply chains, and trade barriers. Due to the interdependence of technologies, businesses need to integrate into increasingly global technological supply chains which span traditional industry sectors.

Governments can influence openness by:

- Enhancing the open-access provisions of publicly funded research and rejecting complaints of commercial publishers who would restrict access to the publicly funded research that can aid technology development and adoption.
- Ensuring public sector data is open to facilitate new technologies that depend upon it

- Ensuring patent systems do not act as a brake to innovation (e.g. adapting systems to mitigate against patent trolls).
- Minimising trade barriers – much new technology originates overseas.
- Designing innovation policy that is not based on existing industry sectors, as to do so will put barriers in the way of inter-industry interaction and will entrench old systems, infrastructures and behaviour.

Attitudes

Technology adoption can be substantially influenced by attitudes, from both business and customer perspectives (Section 5.1.2). These attitudes can be ingrained, contradictory, and tacit. Collective attitudes (workplace cultures and norms) can also have a substantial influence on the adoption of new technology ((Sections 2.9.3, 7.4). Many aspects of technology evaluation are affected by cognitive biases of various sorts (Sections 5.2.4, 6.4.2), and these can influence assessment of technologies and their adoption.

Governments can influence these factors by:

- Modelling good practice in technology assessment, for example, by using reference class forecasting and by taking a broader context into account. If a technology causes some harm, it should be calibrated against other technologies and the harm they cause, rather than viewing the harm of one particular case in isolation.
- Serving as an honest broker for the provision of information on new technologies (recognising that interested parties will not necessarily present balanced evidence).
- Mitigating against negative attitudes to new technology in general (influenced for example by fear of occupational obsolescence) by ensuring that there are effective retraining schemes and social safety nets for affected workers
- Introducing a culture which embraces the opportunities offered by technological change in primary and secondary education and vocational training, so that technological change is expected and welcomed
- Widening the focus of technical education from a description of what presently works, to a deeper understanding of why it works. If workers understand better why things work, their ability to understand and adapt to new technologies will be significantly expanded.

Approach to risk and failure

Technologies are never perfect when first introduced, and thus businesses and industries that wish to adopt new technologies need to able to deal effectively with failures (Sections 2.9, 7.5, 7.6). A risk-averse business will be less inclined to adopt new technologies.

Governments can influence approaches to risk and failure by:

- Modelling best practice when dealing with problems that involve new technologies, and recognising that failure is an inevitable part of learning, improvement and progress.
- Influencing STEM education efforts to ensure that students learn how to experiment properly, and how to learn from and benefit from failures.
- Encouraging universities to offer technology education for all graduates (technology in society for example, where students can learn some common patterns of technological change).
- Implementing programs such as the US Small Business Innovation Research program which enables small businesses to explore their technological potential and provides the incentive to profit from commercialisation.
- Encouraging innovators to experiment with multiple technological options for a given problem, recognising that it is unlikely there is only one solution.

Appropriating economic returns of early stage technology research and development

Businesses may avoid investment in early stage technology development because of a concern of lack of appropriation of economic returns (capturing the financial rewards of an innovation for the innovator), or simply a lack of knowledge of new technologies (Section 7.9).

Governments can encourage early stage technology research and development by:

- Recognising that indirect spillovers from early stage technology R&D have a very large positive long-term effect on the economy. There are widespread social and economic benefits to rewarding R&D.
- Mitigating the lack of appropriation by providing increased long-term stable investment in early stage R&D organisations, which can be done in a budget-positive way when the returns from R&D are accounted for.
- Not requiring government funded R&D organisations themselves to try and appropriate the returns (that gets in the way of technology transfer to industry).
- Encouraging existing institutions such as universities to free up their IP arrangements to enable the IP to be more freely used.
- Facilitating close industry engagement with R&D centres which develop new technologies in order to enhance industry's ability to incorporate new technological knowledge.
- Offering motivating prizes for solutions to challenging problems through the development and adoption of new technologies. For example, the United Kingdom's Longitude Prize offers large sums of money for a solution to a specific problem.
- Considering other innovative solutions from around the world such as Patent Box, a tax incentive of the United Kingdom government, which provides local incentives for the manufacture of new-to-market products and supports research and development by providing benefits to businesses taking a product, process or service from concept to commercialisation.

Market structure

Market structures can hamper business and industry motivation to adopt new technologies (Sections 2.7, 2.9.2). Structures that reduce negative externalities (such as pollution) can only be economically viable if businesses can capture the economic benefits of that reduction. Deeply entrenched monopolies (for example current taxi licences) can serve to discourage new technology adoption by businesses.

Governments can influence the impacts of market structure by:

- Explicitly pricing negative externalities through taxes or fines.
- Monitoring and intervening when monopolies become too powerful.
- Ensuring that market mechanisms such as the national energy market do not implicitly work against innovative new technologies (for example, by having artificially high scale barriers to entry).

Standards and interoperability

Businesses can be less inclined to adopt new technologies in the absence of adequate standards (Section 2.9.2). Standards which facilitate interoperability and market efficiency aid businesses (Section 7.7). Conversely, adoption of de facto standards too early can lock in an industry in a manner that is hard to change Sections 2.5, 7.7.4).

Governments can influence standards and interoperability by:

- Sponsoring the development and adoption of simple, interoperable and (where possible) global standards.
- Monitoring business practice to mitigate against adversarial lock-in via the exploitation of monopolies.
- Promoting the adoption of standards by mandating their use in government procurement of technologies.
- Encouraging the development of gateway technologies that allow multiple standards to interoperate, rather than by default insisting upon single universal (and hence sometimes unwieldy) standards.
- Promoting the use of platform technologies that facilitate the development of other technologies and business opportunities.

Dependence upon infrastructure and other technologies

All technologies rely upon other technologies, and all of the above points apply to predecessor technologies (Sections 2.3, 2.5). New technologies can be held back by the weakest link (e.g. a component, process, system) that is not keeping up with the front of technological advance (Sections 2.6, 3.5.3). This is particularly the case with regard to infrastructure.

Governments can enhance the use of infrastructure and other technologies by:

- Ensuring that infrastructure investments make the best use of existing technologies and services whilst allowing for future flexibility (e.g. simple and flexible standards that allow for interoperability);
- Facilitating knowledge flows about other technologies through enhanced education and training;
- Discouraging categorisation of infrastructure into sectors, instead encouraging cross-overs from different technologies (e.g. to improve the transport network, use computers not just concrete).

Government's role as a purchaser of new technologies

The Australian Government is a major purchaser of new technologies in markets such as defence, telecommunications and agriculture. Government purchasing and investment decisions can directly influence the business opportunities for the adoption of new technologies (Sections 2.9.2, 7.9.3).

Governments can influence this factor by:

- Explicitly recognising the direct power they hold in this regard, and using it as a lever to speed technological development by encouraging the supply of new and better technologies

Q5. What are the opportunities, barriers and determining factors for new or different uses of modern information and communication technologies in Australia?

The factors that affect the adoption of any technology apply to information and communication technologies (ICT). These determining factors can be opportunities in one context, or barriers in another. ICT is a pervasive general purpose technology, which will continue to affect Australia's security, cultural, democratic, social and economic systems (for some examples see Appendix 2: Case studies, [305,306,343]).). Most of the benefits and penalties of ICT are cross-sectoral. Like all technologies, the effects of ICT are not neutral, nor are they unambiguously beneficial or harmful. ICT is unique however in that many of its products are intangible, and it can be applied to problems that at first glance do not appear to be technological, such as how organisations are managed.

ICT is not a sector, just as steam power was not a sector; and electricity infrastructure is not a sector. ICT is best understood as underpinning the long-term transformation of all industries. It is embedded in the whole economy and will transform the whole economy. Its social, democratic and cultural effects are widespread and have significant and complex implications.

The long term effects of the 'ICT revolution' will substantially surpass the effects of the industrial revolution. Economist Robert M Solow famously remarked in 1987 that 'you can see the computer age everywhere but in the productivity statistics' [982] to describe the discrepancy between increasing investment in information technology and a decline in the rate of increase in total factor productivity in the US from the 1970s to the 1990s (although when examined at the firm level the impacts were clear and positive). Perhaps the invisibility of much ICT has blinded commentators to its near-ubiquity across all areas of research and industry over the last several decades, including their widespread use in such diverse products as automobile antilock braking systems, mobile telephones, cinema, printer cartridges, appliances, GPS, and communications equipment. Some of the most important innovations generated by ICT have been service or process innovations rather than product innovation, and hence will be opaque to standard measures of total factor productivity [622]. Lipsey et al. [622] argue that long-term economic growth is largely driven by general purpose technologies such as electricity infrastructure and ICT, and that there are few goods and services in the 21st century that are not made with the aid of computers at some stage during their production and manufacture (Section 3.5.2):

New ICTs have already revolutionised society and will continue to do so well into the 21st century. Some of these are minor whereas others are transforming, such as globalisation and its many ramifications, the dramatic changes in the organisation of firms, the end of mass production and its associated labour and management requirements, the alternations in the political power structure, the emergence of the civil society and its effects on the conduct of international negotiations [622].

ICT is a very broad aggregation of technologies, and one can identify more specialised but still general-purpose technologies within the general category. Two that are having increasing impact are machine learning (or data analytics) and modelling and simulation. Machine learning allows the development of insights from empirical data – it enables the pervasive application of the scientific-empirical method to almost anything. Modelling and simulation are similarly general and enabling – by being able to simulate all manner of systems, from economic through to ecological, it is possible to experiment *in silico* far more widely and far more cheaply. These two new general purpose technologies offer enormous social and economic opportunities for countries which facilitate and embrace their widespread development and adoption.

ICTs are components and enablers of many other general purpose technologies, and underpin many recent developments and innovations, across different sectors, industries and disciplines. They have a powerful effect in combination as 'gateway technologies', which multiply and magnify the network effects of other technologies (Section 7.7.6). An example of this is 'national map', a gateway to Australia's public spatial data. To a user this appears to be an enormous collection of spatial data related to Australia in one place, but it is based on some clever software design that federates existing dispersed data sources in a manner that makes it extremely easy to add new data sources. This innovation exemplifies some key points about the types of ICT innovation that can have a large effect:

- It serves to multiply the value already extant, rather than just adding to it.
- It shows the power of simple and composable standards (the requirements for integration into national map are very lightweight).

- It leverages a wide range of existing leading-edge platform technologies (including in-browser programming frameworks, and distributed map serving).
- It illustrates the agile development method of deploying technology and perfecting it iteratively.

It is easy to envisage other new and different uses of ICT including smart farming, wearables, primary health care apps and AuScope Grid (a national platform linking the major geoscience and geospatial data stores of government agencies with the high-performance computing resources and high bandwidth networks of the academic community). With the right settings, ICT components such as data, modelling, simulation, sensor networks, and machine learning themselves create the environment for these new and different applications e.g. DNA sequencing, smart grids, radiofrequency identification technology, and mobile platforms [881]. This combinatorial strength points to the benefits of looking beyond disciplines, industries or sectors.

Opportunities

The most valuable opportunities of ICT are those whose impact is multiplicative, not just additive. These opportunities are transformative, completely changing the way existing industries and businesses operate. Some examples are listed below, but every industry sector, every business, and every area of government service delivery can be positively transformed by the use of leading-edge ICT.

Computers can model the likely effects of changes in climate on vulnerable coastal environments, and the economic, social, and ecological implications of these changes, as well as test options for remediation and the costs and benefits of different kinds of development.

The challenges of managing food, health, population, urban design, energy, biodiversity, water quality, greenhouse gas balance, and energy are particularly acute in a sparsely populated country like Australia, with the added challenges of remote industries, a variable climate, and large arid and semi-arid regions isolated from urban infrastructure. These challenges become more acute with the hotter, drier climate of many predictive models. A reduction in arable land will put pressure on other assets, like the mineral industry and Australia's unique biodiversity, as well as threatening food security. ICT offers ways to communicate over long distances, improve education (see Appendix C.8 [764]) primary health care in remote and rural regions, and provide sensor networks and data to improve biodiversity outcomes and agricultural processes.

ICT will also underpin the infrastructure of Australian cities including transport (e.g. roads, bridges, public transportation, see Appendix C.3 [931]), utilities (e.g. gas, electricity, water, sewage, see Appendix C.2 [930]), and public and private buildings. The 'smart city' initiatives around the world are aiming to improve the quality of city life while addressing issues of sustainability, energy efficiency and resource management.

There are considerable opportunities for ICT-driven innovation in service delivery. Data analysis may help government agencies to increase productivity and effectiveness by enabling them to tailor and target services, policies and programs with more foresight (see [306]).

Computer modelling and simulation can offer scenarios and options for Australia given a variety of policy settings and climate, population, economic and technological trajectories.

Some of these innovations are possible with current computer power, but the next generation of supercomputers will be needed to improve prediction in complex but important areas of research such as climate and meteorology, oceanography, fluid dynamics, and energy. Better-targeted software, improved networking and increasingly sophisticated data analytics have partly decoupled improvements in modelling from raw computer power.

Barriers

While ICT offers unprecedented opportunities to improve business and public policy outcomes, there are physical, economic, and skill barriers to its widespread adoption.

Australia lacks critical mass in ICT skills in programming, software development, computer engineering and design, data management, data mining, data collection, data analytics, and statistical analysis. If an economy or a community does not have a sufficiently developed community of programmers and designers, its ICT ecosystem may be impoverished, retarding uptake and diffusion of new ICT across businesses, industries and the wider population (Section 7.3, 7.4). Advanced R&D organisations play a crucial role in lifting Australia's game in ICT development and adoption. Schools and universities are beginning to teach skills such as computational thinking more broadly. To be on the leading edge, a skilled workforce is vital. Advanced skills are needed to exploit the latest ICT. These skills are best developed by training people to create, adapt and use the newest technologies.

Government agencies also need to attract workers with diverse skills including training in science, technology, engineering and mathematics subjects, research and analysis, data analytics, statistics, design, management and creativity. This array of skills is unlikely to be found in a single person, so collaborative teams of specialists will need to be assembled to allow agencies to achieve better results.

Like other technologies, ICT depends upon underlying infrastructure. Crucial infrastructure in this case is pervasive broadband networking. Adequately and rapidly dealing with Australia's particular challenges in this regard (a consequence of sparsity of population and great distances between population centres) is essential to facilitate adoption of advanced ICT.

Potential barriers to new and different uses of ICT include a lack of standardisation or poor or restrictive standards, networking and interoperability, and inconsistent, expensive, or hard-to-use storage formats, complicated licensing, IP, anti-tinkering laws, and cost. Encouraging cross-over between diverse areas and looking beyond narrow sectors and disciplines for inspiration amplifies the opportunities for technological parts assembly (Sections 2.5, 7.2). ICT, like other technologies, takes components and processes from elsewhere so disciplinary, industrial, engineering or sectoral silos can impede innovation, uptake and diffusion. Transparent, empirical experimentation is the best response to the uncertainties and complexities of technology change (Section 7.6).

In the social and cultural context, data analytics illustrate social and cultural issues well e.g. genomic data on its own is useful but is more epidemiologically useful when combined with other health and demographic details to improve quality of life. Such aggregation is accompanied by particular data management issues, including how to ensure anonymity of personal information as some data is more 'personal' than others. Developing suitable policies for the proper management of personal data remains a challenge.

Q6. How should all these questions be considered by Government in an ongoing fashion in the future?

The most important lesson from the project is the central importance of technological change to Australia's future prosperity and well-being (Sections 2.2, 3.4.1, 4.1, 7.2, 7.10) and hence ongoing understanding of technological change is key to understanding and enabling Australia's future prosperity. As the report reflects, it is neither the case that technology always shapes society, or vice versa. They mutually shape each other, and any future consideration of the impact of technologies on Australia needs to reflect this fundamental fact.

Another key lesson is that the value of a technology is not intrinsic and depends upon context. This means, for example, that attempting to assess which technologies will affect Australia as a whole is better done at a local level where context can be understood and inform decision making (Chapter 4). Within government, this means within individual departments. The United Kingdom's practice of appointing a chief scientist within each department is a useful exemplar (Section 6.5).

Much of the analysis of technological change, especially in the popular press, ignores historical context and overemphasises the present and the very recent past. This report endeavours to redress that, and shows that general patterns of technological change are likely to recur and – more importantly – to offer insights for interventions. New technologies are typically imperfect at first, their impact takes a long time to be observable, and impacts are hard to predict accurately (Chapters 3 and 4). There is therefore a need to continually review new technologies and how they are affecting Australian society, culture, democracy, security and economy (Chapter 6). This is an exercise that cannot be done once and put on the shelf.

There is compelling evidence for using a strongly empirical method in technology evaluation. Empirical methods are highly valuable, and any future technology evaluations should be strongly empirical. There are a number of common problems which should be avoided in the future (and also offered ways to avoid them), for example mitigating technological inertia due to vested interest by ensuring a broad range of inputs are considered, and not just the current dominant players in a given area (Section 6.4.1, Chapter 7).

Any future consideration of new technological interventions should embrace the findings of Chapter 7, especially with regard to regulation. Technologies emerge into existing regulatory environments and common law can often address any potential issues. In some cases regulations could be modified before contemplating the introduction of any new technology specific regulations (Section 7.8). The way in which technologies are classified is an important factor to consider in devising appropriate interventions, to ensure that intervention targets the right thing.

Given the very long timescales needed to observe the full impact of technological change, government policy would benefit by a similarly long timescale.

Finally, a number of questions arose in the conduct of this report for which the project team could not find adequate and compelling evidence for answers. To that end, the report recommends that research be encouraged into particular issues including:

- What mechanisms are most effective for engaging citizens in informed debate about new technologies?
- What educational approaches are most effective in inculcating technological capability, enhancing adaptability and effective responses to failure?
- How can Australians become better educated about the role of technology and technological change in society?
- What interventions are most effective in influencing negative attitudes to technology?
- Strongly empirical studies of what is actually done in the process of technological evaluation, replicating empirical studies on how cost-benefit analysis is actually used
- Any statistical analysis of technological change seems better done at the fine-grained level (e.g. firm level) rather than at a highly aggregated level (such as nationally), and such fine-grained studies particular to Australia would be valuable.
- It would be helpful to have country-wide comparative data regarding several topics briefly discussed in this report including: skill levels, speeds of adoption, technology usages, attitudes, and various dimensions of the technological ecosystem. Without such fine-grained information it is difficult to reliably generalise from overseas experience.
- Detailed ethnographic studies of how technologies are actually used in practice are very valuable in understanding the adoption and impacts of technology; having such studies done in contemporary Australia would be valuable.

- What are the options to reform Australia's intellectual property rights regime for national benefit?
- What are the factors affecting the development of vibrant technological ecosystems and environments, bringing up to date, and localising to Australia studies such as [389] and [597].

More generally, the report has relied heavily on overseas studies in the many aspects of technology considered. While it is likely that most of the findings can be translated, it would be valuable to replicate some of these studies in Australia.

1. Introducing technology

Technology is everywhere you go. You might think you know what it is and what it is not, or you might not think about it at all. Every human scene is busy with technology – from electrification to animal husbandry; from agriculture to fabrication; from information and communications technology to public health; from building materials to genetic modification; from transport to fashion (see Box 1). How people think about technology affects how they see themselves. How people see themselves affects their view of how the world functions and how technology is created, used, adapted, and intervened upon. Using technology is an integral part of being human and a primary force for economic and social change [733].

Change is a pervasive characteristic of technology systems. Technological development has been the principal driver of economic transformation and a major force for social change throughout much of human history. Economic, social and cultural activity drive technology diffusion, adoption and innovation, all of which take place in an environment of change and uncertainty. This is both observed (for example in economic systems, technological change is the major source of long-term growth in GDP per capita) and historically imagined (for example, in the ways people characterise significant times in terms of the perceived prevailing technology – the Bronze Age, the Iron Age, the Industrial Revolution, the Green Revolution or the Digital Age).

Cultural change is regularly described in terms of technology. Material objects (technology or products of technology) leave a record which informs how history is understood. Technological developments in the past also help explain physiological and genetic changes and differences in human populations. For example, the transition between the Palaeolithic ('old stone') and Neolithic ('new stone') periods describes an observed shift around 12,000 years ago in some parts of the world in the technology of stone tool construction, increased settlement, animal husbandry, and new forms of fabrication such as the potter's wheel [71,76,735]. And the 'Green Revolution' describes a series of research, R&D, and technology transfer initiatives from the 1940s to the late 1960s which increased agricultural production worldwide, particularly in the developing world. The development and distribution of high-yielding cereal varieties, the expansion of irrigation infrastructure, modernisation of management techniques, and the distribution of seed, synthetic fertiliser and pesticide is credited with improving the nutrition of billions of people and saving more than a billion from starvation. Thus cultural change with profound social, economic, demographic and physiological ramifications is marked by tools for food, conflict, clothing, and shelter [794].

Most everyday objects are technological artefacts – a chair, for example, or a magazine, a shoe, a coffee cup, a smartphone. Some have had a gradual but revolutionary effect on human behaviour – fire, for example. Others had a more immediate effect, changing human behaviour over decades rather than millennia – for example, electricity infrastructure, water treatment systems or internal combustion engines. Technology is part of the essence of what it is to be human. As the last few millennia demonstrate, any widespread intervention or change may have consequences that go beyond the economic and social, affecting the very fabric of being human. Understanding the relationship between technology and humanity is central to this report.

1.1 Defining and categorising technology

Writing about technology presupposes one knows what it is, but this is remarkably difficult to define elegantly. A lesson can be learned from Alfred Kroeber and Clyde Kluckhohn who collated 164 definitions of 'culture' [588]. Defining culture is as complex as defining technology.

Writers on technology find the definition of technology similarly complex and slippery [582,600,697]. This report does not commit to a single definition, because any single definition will break in some cases; the most robust seems to be simply 'knowledge of everything—products, processes, and forms of organisation—that can create economic value' [622] – the key point being that technology is a form of knowledge[3].

The limits and possibilities of human imagination constrain and inform the design of technologies (Chapters 3 and 4). The ways in which technologies are collectively imagined shape their development, their reception and their uses, as well as their users.

Technologies are not merely aids to human activity but also powerful forces that give meaning and direction to human lives [1137]. In quite profound ways, technology and humanity are mutually constituted: human actions and decisions lead to changes in the form and function of tools, products and artefacts, while technology changes human beings as well – their behaviour, habits, ways of thinking, bodies, right down to their cells, throughout their lives and the lives of their descendants [113,782,1006,1149,1150]. Technologies are pervasive in everyday life but not always manifest; see Box 1.

Joe at home, surrounded by technology

Joe sits at a desk, swivelling his chair from side to side, casting duelling shadows in the low light thrown by the desk lamp. Before him is a computer monitor. There is a ballpoint pen beside his keyboard, and a spiral-bound notepad full of his handwriting.

Joe's hair is short, neat, and clean. He has straight white teeth with no fillings. He wears multifocal glasses with titanium frames.

On a plate to the left of his computer rest a knife and the remains of an orange, beside a half-finished mug of milky coffee.

As Rocket, the cavoodle at his feet, stands and shakes, the tags on her collar jangle. The dog leaves the room, her nails clicking on the polished floorboards.

Joe hears a ringing sound. Reflexively he checks the pocket of his jacket, to find that his smart phone is flat. He walks across the hand-woven rug to the bookshelf on the far side of the room, picks up the telephone, and says 'Hello?'

Box 1: Technology at home. Every aspect of this scene is imbued with technology – from the titanium spectacle frames, through to the coffee mug; from the rug on the floor to the computer. We are constantly surrounded by technology in our 'human built world' [509].

Technological artefacts, products and processes are collaborative, multigenerational, socially produced projects. From Joe's teeth to his corrected sight, the food he eats, the clothes he wears, the words he uses, the tools he wields and his actions in wielding them, he is wrapped in, named by, walks on, is moulded by, imbibes, engages with, speaks, and embodies technology at every turn. The stainless steel knife he uses provides the same function as a stone flake with a cutting edge, though it is materially distinct from it. The hand-woven rug reflects generations of practice in modern fabric with synthetic dyes. The next-generation smart phone is a 21st century result of the technologies, bits and pieces of gadgetry, and patterns of use of centuries past. Technologies are interdependent and are shaped by human needs and desires, and by rich and connected histories.

---

[3] Hence all technological societies are knowledge societies, and '*Every* human economy has been a "knowledge economy" and not only the contemporary one, which we, in our arrogance, proclaim today.' page 132 of [382]

Classification simplifies description, although the idea that technology is a natural category is fundamentally misleading. Technology can be an object (such as a mobile phone), a component (the transistor in a mobile phone), a process (a production line), a service (electronic banking), a system or network (telecommunication towers), or all of these (the use of the phone as a financial system, for example). In other words, technology is aggregated in different ways. A smart phone (assembled on a production line) is a piece of technology which incorporates a computer chip, which itself is another piece of technology. The networked smart phone provides a platform for electronic banking, which is a financial service innovation. Considered outside this system of relationships, the production line, chip, smart phone, telecommunication towers and electronic funds transfer are five distinct technologies. As constituents of a financial system, they aggregate into a single technology whose many components may be invisible.

The above categorical slipperiness is not a problem peculiar to technology – all categories that are taken for granted break-down or can be re-arranged upon closer examination]; even the most elementary [314]. This is literally true when one considers the categorisation (and organisation) of the chemical elements. In contrast to the common belief that there is a single agreed 'periodic table of the elements', there have in fact been some 700 proposed tabulations, that can be organised as 146 distinct types [661], and even the very concept of an element is not so clear cut – see [936] (page 280). Any attempt to agree on a canonical tabulation of technologies would be infinitely harder and doomed to fail.

Technological categories 'don't stay the same, but are perpetually evolving, growing, squirming out of their definition' [422]. Sociologist S. Colum Gilfillan illustrated this complexity with the case of the television, asking 'Was it already television?' in 1847 when satirically imagined; or at succeeding stages in the development of its components; or not until 1937 when regular broadcasting began? He imagined it may even not yet be television, and wondered whether 'television, at whatever stage', is 'to be counted always as one invention?', a sort of four-dimensional time-travelling archetype, or if something new emerges at particular disruptive moments, captured under the label 'television' which provides merely a general description of function [422].

'Technology' captures a broad selection of things in the world (processes, products, material, structures, information, practices). The term technology might very broadly include groups of similar things such as furniture, clothing, genetically modified organisms or calculating machines. It might be described according to sector, for example, biotechnology, transport infrastructure, public health or mining technology. Or it might describe collective needs or uses such as information and communication, energy generation and storage, fabrication, transport or sanitation.

Technologies are historically and culturally particular. How a product or sets of products is described or aggregated at any time in the past has ramifications for understanding its impacts now. If directly relevant contemporary technologies are the only considerations when addressing a particular problem, it is possible to miss the significance of historical trends and to misattribute causation. This might result in poor regulation and in standards that can impede rather than facilitate adoption and commercialisation, or in failure to capitalise on innovation opportunities from outside the system (Sections 7.7, 7.8). The development of autonomous vehicles and smart phones, for example, depended on pervasive interoperability and creative parts assembly (Sections 2.5, 7.7), drawing inspiration from technologies such as GPS, digital computing, energy storage, data science, and sensor technologies, as well as from their conventional lineages in automotive transport and telephony (themselves parts-assembly processes)[123]. Without these cross-disciplinary or cross-sector influences, even conventional modern driver-operated cars can look very different. To regard a smart phone as only an internet-connected telephone with camera attached misses the multiplicative effects of combining technologies – it fails to recognise that the whole offers a distinctly different product from the parts.

> 'In a sense, Google's self-driving car is more of a parts-assembly project than it is a dramatic new vision for human transport. The company's real breakthrough was bringing together researchers and the existing technologies that underlie their effort – computer vision, digital mapping, and more … the future is less about technologies themselves than it is about the organizations with the means and the will to put them into practice' [123].

Box 2: When is technology new? Technologies that are apparently new are always made up of older technologies, refined, modified and combined in new ways.

Failing to think critically about the ways technology is aggregated means that attempts to evaluate, regulate or intervene in technology will be inadequate. Japanese material scientist Norio Taniguchi coined the term nanotechnology (science conducted at the nanoscale) in 1974. It captures many different products, materials, processes, and functions largely unrelated by their history, use, fabric or content, and united only by scale. Such an umbrella term, while sometimes convenient, hides the idiosyncrasies of any particular nanotechnology product or process. Blind to the disparate histories of nanotechnology's parts, potential users (including developers, policymakers, regulators) might fail to consider whole suites of products or processes on their merits. They might instead assess them with unwarranted optimism or pessimism, depending on their attitudes to the umbrella category 'nanotechnology' (Sections 5.2, 6.4.2).

1.2 New technologies have a past

American economist of technology Nathan Rosenberg said:

> The public image of technology has been decisively shaped by … the dramatic story of a small number of major inventions – steam engines, cotton gins, railroads, automobiles, penicillin, radios, computers, etc. In addition, in the telling of the story, overwhelming emphasis is placed on the specific sequence of events leading up to the decisive actions of a specific individual [906].

The processes of commercialisation regularly remind consumers of the newness and particularity of technological products. Nevertheless, new products which perform an existing function bear reassuringly familiar names: 'smart car', 'smart phone' and 'digital camera'.

At any stage, new technological products develop and are adopted from existing technological artefacts and processes (including the skills required to create and use them). The contemporary self-driving car illustrates this point. Because there were bicycles, horse-drawn carriages, steam trains and engines (and the infrastructure, components and know-how to create, build, and support them), there are now cars [403]. Because there were cars, there are self-driving cars. But this is not a simple, linear story of incremental change from one form of wheeled transport to a newer, improved version of the same product.

Self-driving cars, as cars in general, are and will continue to be influenced by many factors [24,69,624,699,969]. Self-driving cars will inherit many of these factors from traditional cars which are shaped by users [572], communities and cultural representations [104], social practices [875], attitudes[117,1002] and behaviours [92], aesthetics [84,398], public health concerns [1090], regulation (Section 5.1, Appendix C.5), by the networked infrastructure from which modern cities are moulded (including footpaths, roads, street lighting) [321], by urban design [293,490,554,560,791], the availability of skilled technicians and mechanics [126], fuel use [376], fuel infrastructure and corporate monopolies [674], technological lock-in [217], infrastructure pricing schemes [1073], and even the perception of time [1053]! More generally, any transportation system evolves in a complex fashion, depending upon the underlying technological infrastructure [452].

Carolyn Marvin observed a human tendency toward forgetting and foreshortening when people think about new technology. As consumers and users, people fail to recognise the antecedent technology artefacts that constitute and inform 'new' products and artefacts, and can be blind to the skill and craftsmanship that underpins the familiar objects that surround them. Marvin may have overstated the degree to which people are 'surprised by the changes these shifts occasion in the regular pattern' of their lives [652]. It is easy to become accustomed to rapidly pervasive new products, processes and systems. Decades ago it was simply taken as given that one needed to make firm plans well in advance to meet friends, but with mobile telephones in our pockets this is less common. People rapidly assimilate the conveniences and inconveniences of modern technologies into their everyday experience and make themselves 'at home in the world'.

The dynamic nature of technology development means that static models which fail to recognise the inherent dynamism and interconnectedness of technology are often neither accurate nor helpful. If interventions aimed at increasing technology development and enhancing technology-based innovation are constructed on these simplistic models, they are likely to yield little benefit. Technology development and any associated innovation are complex and require a diverse range of skills. Successful adoption, use, adaptation and ongoing support of technology demand abilities and skills comparable to those needed in developing the technology.

1.3 Australia's social, cultural, democratic, security, economic and technology systems

This report investigates the impacts of current and emerging technology on Australia's social, cultural, democratic, security and economic systems. Elements of these systems are characteristic of, but not necessarily unique to, Australia: technologies and their impacts are global. Opportunities or solutions to practical challenges will not necessarily be Australia-specific. A non-parochial perspective is critical. The domains broadly encompassed by these systems are outlined below.

Australia's social and cultural systems include its federal history, government and industry, the interrelated public and private institutions (for example, state and private education systems, public and private hospitals, universities, banking systems, cultural institutions), the welfare structure, and the formal and informal networks and customs. The social system is historically determined and largely inseparable from Australia's cultural system. These systems encompass a nested set of local, regional, state and national identities. They include multiculturalism, migrant and Indigenous cultures, settler cultures, rural/urban cultures and identities, the cultures of business and industry, and recreation. The social and cultural systems are memorialised, contested and celebrated in archives, state records offices, museums and galleries, shrines, memorials and halls of fame which collect, preserve and create the artefacts of Australian cultures. The funding of institutions that preserve, create, curate and memorialise Australian cultures is evidence that cultural identities are socially valued and constitute a part of Australia's social system. Recognisably Australian icons include natural landscapes, buildings, other pieces of material culture, celebrities, songs, poems, and rituals. Stereotypic or recurrent themes include the beach, the bush, the outback, the inland, farmers, sport, footy, cricket, the 'fair go' (enshrined in legislation), battlers, diggers, miners and drovers.

Because of its history, Australia's social and cultural systems overlap significantly with its security and democratic systems. The national culture is heavily influenced by its history of British settlement. English is the national language (though there is no official language), and the British monarch is also the Australian monarch. Nineteenth-century migrant Christianity (in particular Anglicanism and Catholicism), overlain by the practices and religions of other migrants and a strong thread of secularism, continues to affect Australia's social and cultural practices. Australia's political systems bear many of the marks of 19th-century British political culture, and of colonial cultures before Federation in 1901.

Australia's democratic system broadly describes its systems of governance: a constitutional parliamentary democracy and constitutional monarchy with three tiers of government (federal, state and local) and three arms of Federal Government (legislature, executive and judiciary). Australian democracy is heavily influenced by Australian federalism. State and Commonwealth roles and powers are specified in the Australian Constitution. State governments have their own constitutions. Section 4.3.4 addresses 'impact on governance' rather than 'impact on democratic system' because the institutional structure of Australia's system of governance is the relevant characteristic in this report.

Australia's security system includes local, state and federal agencies and organisations. Together, these secure Australia's boundaries, national and military security, sustenance of its population, energy and resource needs, social safety net, public health and freedom from disease or injury, education system, financial services, online activities, cybersecurity, and environmental health. The web of rules, regulations, legislation, and custom that weaves through these agencies ties them to the behaviour of Australia's citizens.

Human security is at the heart of national security. It includes individual and communal wellbeing, freedom of expression, freedom of religion, security of shelter, income and nutrition, environmental, energy, and food security, and the rule of law. Security encompasses many aspects of human existence: physical security (e.g. the state of being free from danger, threat, illness or injury, and of having reliable sources of food and shelter), psychological security (e.g. the state of feeling safe, stable, and free from fear or anxiety), and way-of-life security (e.g. the safety of a state or organisation against criminal activity such as terrorism, theft or espionage). Human security includes the measures taken to ensure the security of people, infrastructure, organisations, institutions and the state. Technology has significant effects, both beneficial and detrimental, on all aspects of security.

Australia's economic system. Australia is a small market, in which large multinationals are given to experiment. Australia's economic system includes the production and exchange of goods and services, industry structures, financial institutions, regulations, capital, the labour force, market structures, and the extent of consumer sovereignty. All of these elements can be affected by technology and can in turn influence the development and adoption of new technologies.

1.4 Method

The report investigates how technology changes, whether these changes can be predicted, what the consequences or impacts of those changes might be, what technology means to people, ways to evaluate and make technological interventions. The diversity of the project necessitated a diverse methodology building upon disciplinary expertise spanning Australia's four national academies. Drawing on historical writings (but not primary sources), literature survey and consultation, the report investigates the roles and impacts of technologies in Australia on the social, cultural, democratic, security and economic systems detailed above. While the project was originally motivated by a desire to forecast future technologies and their impacts, as the report will demonstrate, this is very hard to do with any accuracy over a long timescale.

Observing that much that is written about *future* impacts of technology pays little attention to the past (and rarely are future prognostications evaluated retrospectively) the report has paid substantial attention to the history of technology, not because it is believed that future technological change will be 'just like' the past, but rather in order to attempt to avoid many of the mistakes made in the past regarding technology prediction:

> As we anxiously ponder our destiny on the eve of the twenty-first century, striving to understand and manage technologies of fearful complexity and danger, an understanding of how people in the past thought about technology and the future may provide useful insights and even a modicum of humility [207] (page 228).

This historical perspective necessarily stretches the scope further since as Rosalind Williams has put it 'the boundaries of technology are unusually obscure' and there seems little compelling way that one could distinguish the history of technology from history more generally [1133]. We have taken the advice of Williams to 'resist the habit of identifying technology only with external objects.' By paying particular attention to the subjective aspects of technology – what it means to people and how it is imagined, because this plays a significant role in how technologies evolve and are adopted (see Chapter 5).

Although there is much empirical data about the topics studied, such data is contestable in the sense that it matters *what* you measure. For example the question of the speed of technological progress depends upon *what* one measures – merely counting patents is far from adequate, see Section 3.3.6; 'innovation' more generally is just as difficult to adequately measure [573,895]. 'The problem of measurement' looms large when one considers technological change from an 'ecological' (i.e. interconnected) perspective. This problem of measurement was examined closely in an appendix to [559], a US report from 37 years ago that is close in spirit and coverage to the present report.

In the language of Boyer [132], the report is an exercise in the scholarship of *integration*, rather than the scholarship of *discovery*. The report does not try to present a scientific theory of technology. It tries to avoid over-generalisations one can find in the literature[4]. Nor does it present new empirical findings. At most it aspires to 'explanations and mechanisms' [329]. It attempts to weave a diverse set of disciplinary perspectives into a coherent whole. In doing so the report takes an historical approach and reviews earlier analogous studies. The most significant and substantial are:

- *Technological trends and national policy including the social implications of new inventions*, a 1937 report to the US president [745] (this was three times the length of the present report);
- *Technological Innovation – A critical review of current knowledge*, a 1975 report sponsored by the US National Science Foundation [895]
- *Technological change in Australia*, the four-volume 1980 Myers report by the committee of inquiry into technological change in Australia[5] [200];
- *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, a US report (from their National Academies), which examined how technological innovation works in different industries and the various factors affecting it [597].
- *Developing Long-term Strategies for Science and Technology in Australia*, a 1995–96 report by ASTEC (Australian Science, Technology and Engineering Council) [53,54].

Additionally the project examined a selection of contemporary industry reports:

---

[4] Consider for example Robert Gordon's influential claim that technological progress is slowing, with dire economic effects [438], or the equally influential 'hollowing-out' premise that artificial intelligence will destroy the middle classes [145]. There are compelling counters to both of these generalisations – from renowned economic historian Joel Mokyr [712], economist James Bessen [109] and from Robert Atkinson [43] respectively (confer also [868]). We do not claim that no general patterns are discernable – they clearly are on sufficiently long time scale (e.g. [382,887]); just that caution needs to be exercised in jumping to conclusions in the short term.

[5] The Myers report is certainly the most substantial report conducted in Australia on technological change. It was widely criticized [294,802,975] most witheringly by Michael Carter [165]:

> On the whole, the recommendations of the committee are an innocuous potpourri of good wishes and pious thoughts. Many call for new committees, larger committees, or new names for old committees. Many more call for further study by these new committees, or by existing committees. … The report is weakest in the two areas where the need is greatest – education and retraining, and the protection of privacy.

We have certainly avoided the recommending of the creation of *any* committees, and fervently hope our findings are more than a potpourri of good wishes and pious thoughts! And we have made quite specific findings regarding education and training.

- *The shift index – uncovering the logic of deep change* [456]
- *Why change now? Preparing for the workplace of tomorrow* [263]
- *Technology, media and telecommunications predictions 2014* [266]
- *University of the future – a thousand year old industry on the cusp of profound change* [335]
- *Ten IT enabled business trends for the decade ahead* [667]
- *Internet matters – the Net's sweeping impact on growth, jobs and prosperity* [668]
- *Manufacturing the future – the next era of global growth and innovation* [645]
- *Disruptive technologies: advances that will transform life, business and the global economy* [644].

Thirteen working papers were prepared and are available online:

1. Bottling sunlight: using energy storage technology as a lens to view the factors affecting technological change in the electricity supply industry
2. Collective technologies: autonomous vehicles
3. Digital computing, modelling and simulation
4. Evolution of Education – How societal readiness and technological improvement is improving online higher education access and quality worldwide
5. From Frankenstein to the Roomba: The changing nature and socio-cultural meanings of robots and automation
6. Future Technology Overview
7. Genetically modified crops: how attitudes to new technology influence adoption
8. Locked into the car: How a vision of unfettered transport freedom transformed personal mobility and reshaped the world
9. Printing the future? An analysis of the hype and hope of rapid prototyping technology
10. Technologies for Data
11. Technology and work
12. Tinkering With Technology: Examining past practices and imagined futures
13. Performance based research funding – an overly simplistic technological intervention.

These working papers have both informed the report and are cited within the report. They contain substantial additional material and delve deeper into particular questions arising from the report. Some of the working papers are summarised in Appendix 2: Case studies.

We are unaware of any previous study that has attempted to draw together such a diverse set of disciplinary perspectives relating to technological change at a national level; the closest in spirit (but not breadth) is *Technological innovation: A critical review of current knowledge* [559]. Such disciplinary breadth seems essential in understanding the complexities of technological change. Ultimately, the report attempts to present effective ways to think about technological change, and how Australia can adapt to it, embrace it, and derive the maximum benefit from it. The answers are not simple, and they are not entirely technological. Technology is not only the preserve of the technologist.

The remainder of the report is organised as follows. Chapter 2 considers how technologies change; who is involved in technology emergence, adoption and diffusion; and how the Australian workforce can deal with the uncertainty inherent in technological change. Chapter 3 examines the prediction of technology, what it means to predict, and offers a new way to frame prediction of technologies. Chapter 4 surveys the impacts and consequences of technology changes and choices; a detailed table of technological impacts is presented in Appendix 1: Understanding impacts. Chapter 5 looks at how technology is imagined and experienced, the relationship with values and beliefs and attitudes to technology and risk. Chapter 6 examines how technology is evaluated. Chapter 7 considers ways to intervene so Australia can prepare for, and capture benefit from, technological change. The chapters underpin the findings outlined in the *Summary and Findings* and the *Answers to project questions*.

2 The shaping of technology

Summary

Technology shapes society and society shapes technology.

Many people play a part in the formation and adoption of technology. The skills to use, adapt and create technology are key to Australian prosperity.

Viewing technological change as an evolutionary process provides insights into many of the phenomena seen in technological change.

***New* technologies are created by modifying and combining *existing* parts and processes in new ways.**

Technology development is facilitated through compatibility, standards, parts assembly and interoperability.

Throughout history there have been concerns that technology is changing faster now, but it is not clear that this is currently true.

The disruptiveness of a technology is not intrinsic to the technology itself; the disruption occurs via the technology's impact.

Radical disruption can arise from gradual evolution of technologies reaching a point where radical impact does arise.

Technological change is inherently uncertain, and this has profound implications for technology prediction, investment in new technologies, and any intervention relating to technological change.

Technologies change through many interconnected factors where human activity and social change contribute to the process of changing technology and human beings change as a consequence of technological change. Technology is shaped through the process of invention, innovation and diffusion, also known as technological change [730]. Social structure and context shapes how people use and modify technology, and in turn the use of technology shapes its social context. For example, the diffusion of the telephone has led to dramatic change in social norms and technological applications over time and continues to do so as both the technology and the societies that use it evolve together (Box 3).

Electric voice-transmission devices were introduced in 1844 after many failed attempts until successful experiments with electromagnetic telephones by Alexander Graham Bell and Thomas Watson finally led to commercially successful telephones in the late 19th century. The telephone led to a completely new form of communication with profound effects, giving people the ability to transmit their voices over long distances for the first time. At first, the use of the telephone was at odds with social norms. Early telephones were always turned on (i.e. the line was permanently open to parties at either end) but at the time it was not acceptable to start a conversation without first being introduced, 'How would anyone know that the other party wanted to speak? Edison addressed the issue as follows: 'I don't think we shall need a call bell as "Hello!" can be heard 10 to 20 feet away. What do you think?' [449]. And so the word hello persists as the conventional telephone greeting in English[6].

Box 3: The telephone has shaped society and social practices

Technological change is enormously important because it is the major driver of long-term economic growth [703,986]. As economist Paul Romer observed, economic history and current

[6] The impacts of the telephone during the 20th century are immense, affecting patterns of human settlement (you can not have skyscrapers without them, as there would be inadequate lifts for messenger boys), the economy, polity, emergency services, resource use and environment, complementary services, system development and social structure [843].

events demonstrate that 'discovery, invention and innovation are of overwhelming importance in economic growth' [900]. This is not to say that other factors are irrelevant, having appropriate institutions and 'social capability' are also crucial [221,915].

Almost everyone is involved in developing, modifying, adapting and using technology. Innovation arises from diverse actors in many different ways. The roles of designers, makers and users overlap and change over time:

> Engineers design technology, managers produce it, salespeople sell it, tradespeople distribute it, users use it. Alas, this neat and orderly image of technical development, so pervasive in all but the most recent technology studies, is not only too simple – it is wrong [116] (page 75).

The design and adaptation of technology is not solely the result of activities undertaken by inventors and engineers. The combined skills and know-how of many people and institutions – users, makers, designers, and firms – produce and change technology [1104-1106]. People are involved in technological change at various stages of technology development with various sets of skills. For example:

- By research and development (e.g. the development from rotary-dial telephones to smart phones, or the academic peer to peer communication (ARPANet) which was the precursor of the internet);
- By commercialisation (e.g. providing electricity infrastructure to the home);
- By crowd-sourcing information (e.g. citizen science);
- By using technology (e.g. consumer feedback and adaptation of technology);
- By tinkering (e.g. the adaptation of bicycle components made the first cars; software development, programming and mobile apps).

The diffusion of a technology makes it available for further change through input from the wider community. The fluorescent light bulb, for example, first produced by General Electric Laboratories in 1938, has undergone many changes to reach its current form (which itself is not static). Light bulbs were modified not only by inventors and researchers but by producers, distributors and end users. In order to make lights suitable for use in homes and businesses, lighting fixture manufacturers developed the auxiliary technologies required such as sockets and reflectors. Customers then helped set the optimal tone and level of light for the home through customer feedback surveys. This example illustrates the interconnected system of people and institutions involved in the development of a widely used technology [511].

Consumers have a long history of tinkering with technology to fix a product, make an improvement or simply just for fun. Consumers tinker on a wide range of things including cars, bicycles, clothing, recipes etc. A recent example of the iterative nature of the development of new technology comes from the mobile app market, whose massive growth over recent years indicates the willingness of users and consumers to modify and create new technologies (Appendix C.9 [542,816,1105]).

Technological change, the invention, innovation and diffusion of technology, can happen in many ways including:

- **New combinations of existing technological components** producing little change in function. Books, for example, whose form and function have hardly changed from the Roman codex or a medieval illuminated manuscript, but whose production, materials and circulation have changed drastically.
- Creation of a technological artefact by **combining existing technological components in a new way to perform the same task** (a desk lamp using LED lights and polymers instead of incandescent bulbs and aluminium, for example) or perform a new task (punch cards previously used for automated weaving were later adapted for data storage in digital computers).

- **Incremental change** of one or more components combined with existing components to create a new technology (the first smart phones, for example, combined functions which were previously found in separate products).
- **Gradual modification** of a technology artefact over relatively short periods of one or two years (a new version of the iPhone operating system software, for example).
- Emergence of **technologies that depend on advance in other technologies** – to some extent this can be circular (for example, advances in computational processing power require improvements in digital storage capacity, leading to increasing amounts of data, thus requiring further advances in computational processing power and digital storage capacity [305].
- **Combination** of many components, processes and systems to create socially-mediated technological systems (sociotechnical systems) such as electricity, energy and telephone infrastructure, which can take long periods of time to diffuse pervasively.
- **Change in the use** of a technological artefact from one application to another (computers, for example, were originally designed as bespoke calculating machines and are now in cars, phones, buildings, and washing machines).

In order to improve how technology and its impacts are anticipated, evaluated and managed, it is important to be aware of the complex system and varied players involved in technological change.

2.1 The speed of technological change

Concerns about the pace of technology adoption and its implications are not new – the very name 'industrial revolution' signifies rapid change [382,598,673,711], and it certainly appears to have been a time of 'acceleration of change' [478](Chapter 7). While some perceive a speed-up of technological change in the last decades, an historical analysis suggests otherwise. The pace of change can be measured via technology adoption rates, although this is complex and problematic (Section 6.1). To understand the pace of technology adoption, especially given the complex ways in which technology can be aggregated (see Section 1.1), measure the adoption rate of technologies should attempt to: compare like with like whenever possible (e.g. device with device or infrastructure with infrastructure); and understand where a technology comes from, when the technology was invented, when it became commercially available, and when and where it was widely adopted. For example, adoption of household electrification and the personal computer in the US both show similar rates of adoption (Figure 1). Measuring electrification in terms of households obtaining an electric service (from 1894 -1929) and the availability of the first PC (1971- 2003) shows that households adopted electrification approximately as rapidly as they adopted the PC [539].

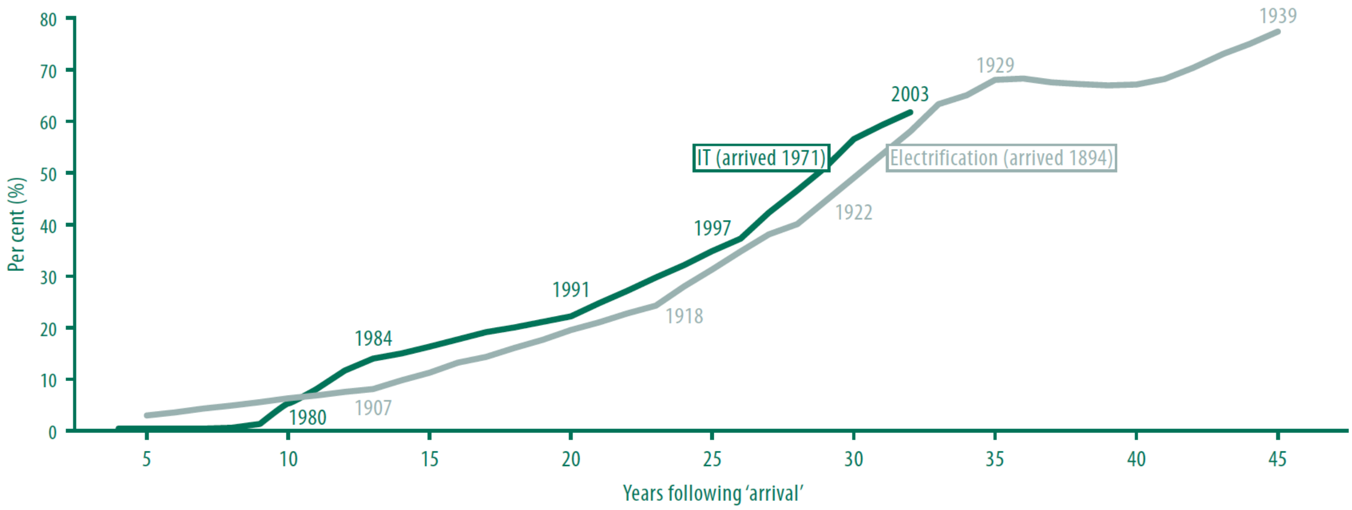


Figure 1: Percentage of households with electric service and PCs during the two general purpose technology eras. Reproduced from [45].

Some scholars have claimed that the average speed of technology adoption is faster now than it was in the past: 'The speed of convergence for technologies developed since 1925 has been three times higher than the speed of convergence for technologies developed before 1925' [199]. This conclusion makes the story seem much simpler than it is – inspection of figure 21 of [199] shows that there is enormous variability hidden behind such simple conclusions. The difficulty is that there are many different factors. For example, measuring the pace of technological change and adoption is complicated by when one declares a technology to exist[7], or the level at which technology is aggregated. Technology can be aggregated at the level of component (chip), device (phone), system (internet) or discipline (ICT). Depending on the number of components in any given technology, each component will change at different speeds complicating any predictions or measurements (Section 3.5). A further complication is that if older technologies continue to improve, then new technologies are less compelling, and thus may progress more slowly:

> The speed with which new technologies are introduced is also heavily dependent upon the speed with which the older technologies continue to move along their own improvement trajectories [911].

Very broadly speaking, technology devices (such as a smart phone or television) achieve widespread adoption over a period of 10 years; infrastructure adoption (such as electricity and telephone infrastructure) on the other hand can take 30 years (Figure 2 and Figure 3). Technological devices or processes that can take advantage of existing infrastructure will be more likely to diffuse over years rather than decades (e.g. the recent adoption of smartphones was greatly aided by the pre-existing electricity and internet infrastructure). This phenomenon is particularly manifest with software, which due to its incorporeality has less inertia, and it often does not require substantial infrastructure changes, so can diffuse much faster. This is why software has become such a rapidly growing part of technology [963] – the software in a system can be changed far more rapidly than the underlying hardware.

[7] The precise moment of invention is difficult to determine, and the point of economic feasibility depends upon many factors – seethe chapter *The conceptualization of technological innovation* in [913].

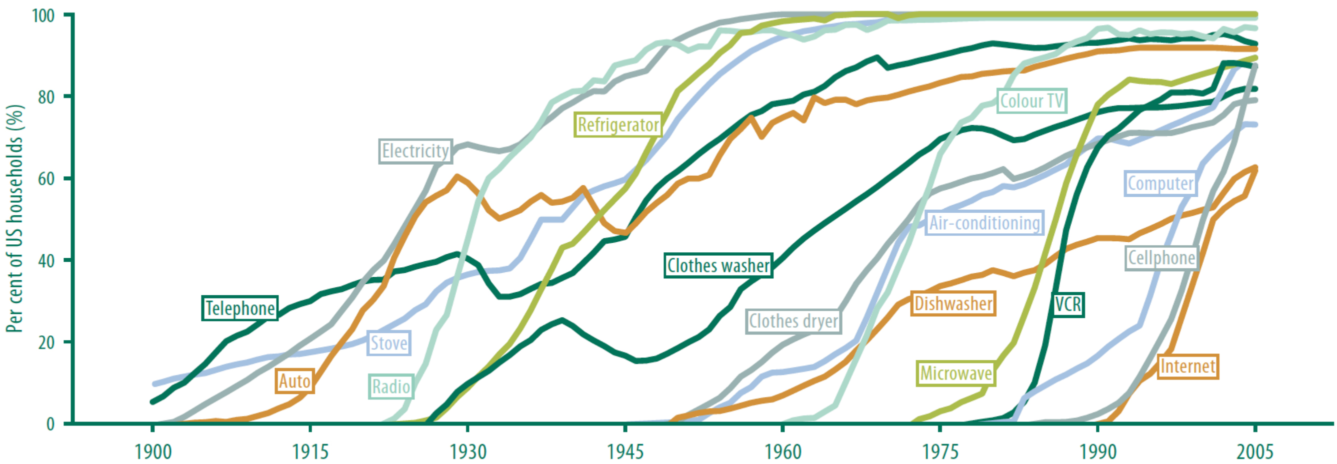


Figure 2: Percentage of US households adopting various technologies over time, including technology artefacts and infrastructure. Reproduced from [354]. Note that the degree of aggregation listed varies from device to infrastructure. The original figure had a headline that said 'consumption spreads faster today'; it would be more accurate if it instead said 'consumption spreads faster when the infrastructure is in place'. Without the supporting infrastructure it is difficult to access electricity. With the availability of electricity then adopting a microwave for example is easy. Furthermore, using this graph to compare the dishwasher and radio one could conclude that 'consumption spreads slower today'. The sorts of very general conclusions often to be found in contemporary discussions of technological change regarding the 'goodness' or otherwise of the current crop of technologies are suspect for a similar reason – they overgeneralise.

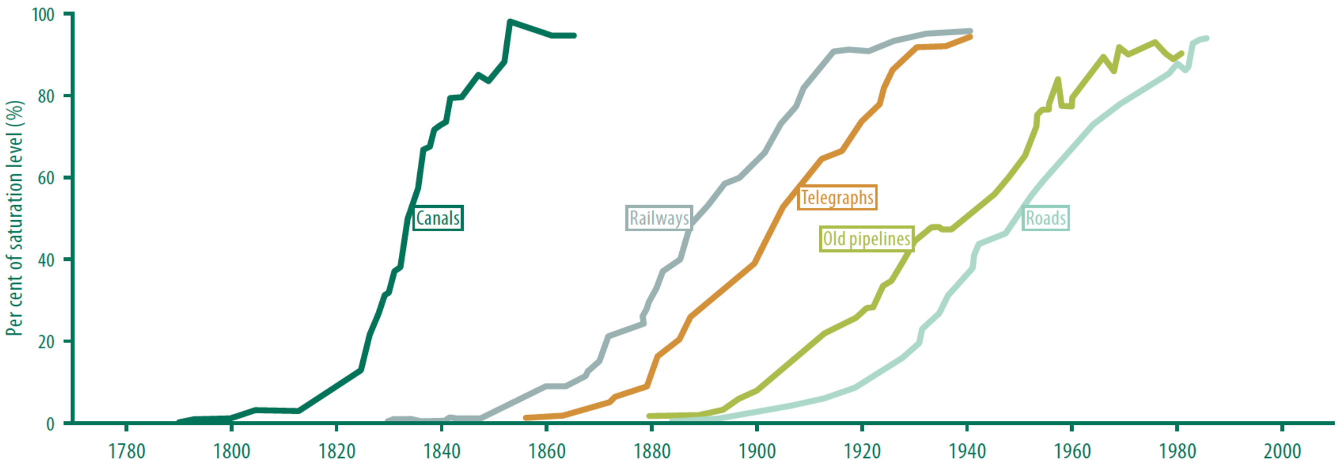


Figure 3: Infrastructure technologies spread relatively slowly, at comparable rates over a long historical period, reflecting the inherent momentum and inertia of changes to infrastructure. Graphs show the rate of penetration, where the 100% level is determined [454].

At a high level of aggregation, general purpose technologies are technologies which are widely used across the economy, with many different uses and spillover effects, that can augment or complement existing or emergent technologies [622]. General purpose technologies (see Box 12) are significant for their ability to spread across most sectors, improve over time, support new innovations and as a result change the way households and businesses work. Internal combustion, steam and electricity are often classified as general purpose technologies, and the transformative effect of electricity infrastructure has resulted in economic growth and improved living standards [539,622,917]. Information and communications technologies (ICTs) are general purpose technologies that are have had substantial impact in the past[8] but have been particularly economically and socially transformative during the 20th and 21st centuries. Their effects have been even more marked following the widespread adoption and diffusion of programmable digital computers:

> Over the past forty years, computers have evolved from a specialised and limited role in the information processing and communication processes of modern organisations to become a general purpose tool that can be found in use virtually everywhere, although not everywhere to the same extent ... computers and networks of computers have become an integral part of the research and design operations of most enterprises and, increasingly, an essential tool supporting control and decision-making at both middle and top management levels [248].

The impacts of ICT are contested, including the scale of these effects, or even on whether ICT has led to productivity improvements. However when the impact of ICT is measured at the level of a firm or business, it is clear that ICT does improve productivity [784,857]. However measuring the impact of ICT on productivity growth at the national level is more challenging, particularly as the technology becomes more pervasive [888]. This implies that if one only works with highly aggregated statistics one will not be able to understand the true factors affecting the diffusion of technology.

Mass adoption of smart phones (devices) was greatly aided by the almost ubiquitous availability of telephone and internet networks (infrastructure), however widespread infrastructure can also act as a barrier to technology development. For example, the combined effect of the pervasive network of roads, petrol stations, existing policies and widespread social gains from the use of the car may impede the adoption of fully autonomous vehicle technology, because of the considerable sunk cost in existing infrastructure, and significant vested interest (Section 2.7). Also, dependence on fossil fuels and its centralised energy system with entrenched business models, has acted as a barrier to the development and adoption of renewable energy technologies (see Appendix C.2 [930]).

Ultimately arguing whether or not technology adoption is faster now than it was in the past achieves little. It is more valuable to understand the reasons for different rates of technology adoption.

2.2 The emergence, adoption and diffusion of technology

The process of technology development, adoption and diffusion is too complex to understand without some model or theory of how it occurs [738]. The models, theories and even language used to describe innovation and technological change influences the way people understand technology, inform how technology is evaluated and how interventions are designed (Chapters 6 & 7).

Models of innovation have evolved over the years – long enough ago the very notion of innovation as a thing to be desired was rare [431]. The whig-historic notion of unidirectional ‘progress’ [154] led naturally to so called linear models of technological innovation ‘that innovation starts with science or basic research, then undergoes applied research, followed by development and commercialisation’ which has been extensively critiqued since its introduction in the mid 20th century [432,433]. Linear models can obscure the complex origins of technology; new technologies can arise from fundamental scientific advances (radio relied upon the physics of Hertz and Maxwell), user demands (the evolution of mobile phones and associated products) tinkering (backyard hobbyists designing their own apps), the combination

[8] The clock is a type of information technology (its sole purpose is to provide information – the current time) that has famously been credited with a greater impact on the modern world than the steam engine [733]; see also [794]. Other information technologies such as bookkeeping and advertising have played similarly large roles [102].

of different existing technologies (a mobile phone makes use of diverse advanced materials, electronics, software, signal processing, wireless and cryptographic technologies, for example) and typically depends upon of all of these. Any given technology is a combination of many pre-existing technological components or processes. iPhones, for example, are made up of over 10,000 components with ancestry in ICT, advanced material science, chemistry and many other disciplines and sectors. Understanding that technology can derive from a parts-assembly process helps explain that the outcomes of any technology or product are inevitably affected by the product's history, its uses and interdependencies (Sections 2.3, 2.5). Furthermore, as illustrated in Chapter 5 and Section 7.3, different people have different motivations to adopt technology: users may want a technology because it will solve a problem, investors want to make money, and inventors are often simply following their 'instinct for contrivance' and joy of creation – a fact recognised a century ago in books such as *Inventors and Moneymakers* and *The instinct of workmanship* [1030,1093]. Some models recognise this multidimensionality explicitly [1010], others, such as the linear model of technological innovation, do not.

Simplistic concepts behind the above mentioned linear models still exist in policy debate over how public funds should be allocated to support innovation in specific sectors. Noting it is extremely difficult to design and implement policies based on complex and interconnected systems, it is crucial that policy is based on the understanding that technology, the economy and Australian society are interlinked and shape one another, and that most technology change is gradual and evolves in a complex and interdependent environment [63,433]. Demand can inspire the creation of technology; technology can generate demand; technology change results from feedback cycles (more powerful computers need more software, for example, and vice versa); and motivations to produce and use technology change over time. Models, such as evolutionary ones, which attempt to account for the complex interdependencies that exist in innovation and technology change are likely to produce more accurate depictions of technology change, and consequently better guide interventions (Section 2.3).

There is a temptation to create simple 'mono-causal' or monistic models that reduce the complex process of technological change to an overly simple theory. The historian of technology David Landes' suspicion is valid, 'nothing rouses his suspicions faster than the monistic explanation' [11,598], (page 535). Such monistic theories have been proposed to explain societal and cultural change[9]. As is true for society and culture, there is no simple single theory that explains everything about technological change.

Technology innovation is sometimes described using the market-demand (pull) and technology-push model. Market-pull refers to the need for a new product or a solution to a problem identified from the market. The need is identified by potential customers or market research – 'necessity is the mother of invention'. Technology-push on the other hand is when research and development in new technology drives the development of a new product – 'invention is the mother of necessity' [1093] (page 316) - the canonical example is the laser (Section 3.3.1)[10]. The idea that technology and the market are separate and opposing forces has been widely criticised; both supply and demand factors are required to explain innovation, they interact with each other [433]. Many important innovations are not only not the result of market research [1028], and many innovators explicitly disavow its use [1095].

The pull or push models have implications for skills and R&D focus – as outlined in Section 7.3 many technologists are driven by intrinsic motivations, and so the market has little pull on them. Furthermore R&D that leads to more substantial technological benefits is frequently motivated by intrinsic technological challenges (technology push) rather than market pull

[9] See the table on pages 4-5 of [102]

[10] Neither the push or pull model fully explains past-developments [297], for example the development of the computer industry appears to be sometimes better explained by demand pull [331].

(Section 7.9.3). Although economic forces and motives have inevitably played a major role in shaping the direction of scientific progress, they have not acted in a vacuum, but within the changing limits and constraints of a body of scientific knowledge [905].

2.3 Evolution of technology

In the same way that cultural change is well explained as 'cultural evolution' [288,351,684] so too is technological change nowadays understood as technological evolution, rather than technological 'progress'[11]. Such a theory does not try to explain everything, but it is helpful in conceptualising technological change – technologies change through an evolutionary process [302,303].

'Evolutionary' means any process involving *multiple entities* (for example different technologies or biological species), a process for *novelty generation* (creativity of inventors or random mutations in the genotype), a process of *combination* (re-use and borrowing of technological components or sexual recombination of genotypes) and a process of *selection* (market forces or the overall biological environment). Technological evolution is not an analogy to biological evolution. They are both instances of the same logical schema (multiple entities, novelty generation, combination, and selection), which has multiple and profound consequences for understanding technological change. A key difference between the evolution of biological species and the evolution of technology is that the phylogenetic tree or 'tree of life' in the case of technology (or for that matter any cultural artifacts) has no unique path from an arbitrary 'leaf' to the 'root'– an observation made by anthropologist Alfred Kroeber – see Figure 4.

[11] In the past, technological change was tightly tied to the general notion of progress, a recurring and popular theme in the history of Western civilization; Sidney Pollard [839] lists 14 other books entirely focused on the idea of progress, and there are many more [154,887].

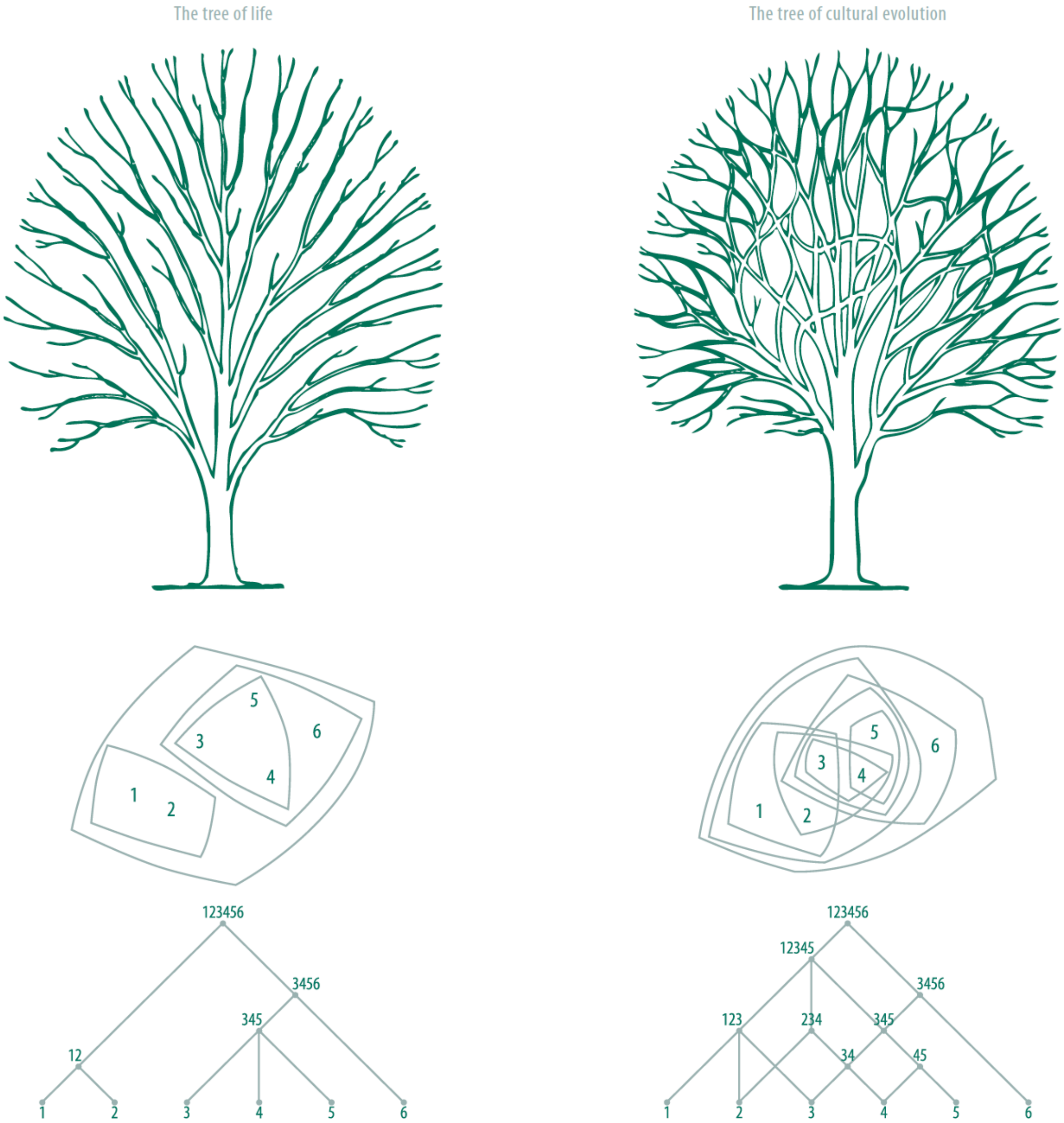


Figure 4: From left to right: The tree of life, where hybrids are rare (top left) and the tree of cultural evolution where hybrids are the norm, which includes technology as a cultural artefact (top right) page 269 of [587]; hybridization (the joining of branches) through reuse of older technologies as parts of new ones, is central to the evolution of technology. The complex interdependences that are generated by such tangled histories underpins the complexity of much of the human built world. The middle and bottom images illustrate the abstract tree structures and more complex overlapping histories – technologies are, like cities, not a tree (from [16]).

Viewing technological change from an evolutionary perspective is not new; as an explicit theory it dates back at least to Eilert Sundte in 1862 (see [328]), only three years after Darwin's *Origin of Species*. Nelson and Dosi [302] quote Bernhard de Mandeville, who perceived in 1714 the incremental evolution of complex technologies (in his case a warship). Nowadays widely accepted as a valuable way of viewing the dynamic complexity of technological change. The evolutionary model of technological change explains how technologies change through the gradual improvement, adaptation and combination of existing technologies and the role of selection (by the individual, group or market) leading to novel products, artifacts or processes [82,299,508,686,705,759,1158]. Given the centrality of technology to economics, evolutionary approaches to technology share much with evolutionary theories of economics. This helps explain the observed dynamic economic phenomena such as Schumpeterian 'creative destruction' or 'transformation'[12][686,760] so important to the economic impact of technological innovation.

The evolutionary theory captures many of the features of technological change including: the parts-assembly process [35,1091]; path dependence [66,82,156,190,302,923]; the dynamics of regime shifts [731] and infrastructure change [452]; cross-over between types of technology [695,980]; the interdependence between technologies [12]; the evolution of networks [246], systems [403] and paradigms [822,826]; successive financial crises and cycles [823,824]; the co-evolution of industrial structure, institutions [755,1066] and society [401]; the co-evolution of technological categories [450]; the complexity of associated economic effects [28]; how technological learning occurs [301]; the selection process which depends on the broader environment [82]; the uncertainty of technological innovation [365], and the appearance of punctuated equilibria (which originated in biology [439]) in the development of technology whereby the apparent rate of progress is highly variable [756]and sometimes stalls [206,382,411,612,626,704,826], as well as the construction of niches [944].

Biological evolution progresses at an uneven tempo (as 'punctuated equilibrium'). In the same way that there is no necessity for external influences to explain this phenomenon [762], one can understand the variability of speed of progress in technological evolution as largely caused by the interdependence of technologies. A gradual change in the component cost of a technological system, for example the cost of fabricating photovoltaic cells, can lead to rapid changes in rates of adoption when the 'adaptive fitness' of the technological system thereby passes a threshold, such as cost-effectiveness against entrenched modes of generation of electricity.

The evolutionary model of technological change makes sense of technological inertia and resistance (Section 2.7):

> Every act of major technological innovation, then, is an act of *rebellion* against conventional wisdom and vested interests, and thus will normally lead to some kind of resistance. Technological resistance has a number of different sources and mechanisms but it is a property of *all* evolutionary systems [708] (page 12).

The evolutionary perspective on technology change offers novel and useful insights for policy makers [687,1087]. It emphasises the value of multiple approaches, the irreducible uncertainty, and the power of recombination and modularity, which is central to technological innovation [66,410,485,599]. Policies that facilitate greater modularisation of technology are likely to accelerate the evolution, development and hence adoption of the technology (Section 7.7.2).

The evolutionary approach explains the path-dependent nature of technology [240,243,245,296]. This helps one understand the extent to which new technologies owe their existence to, and indeed are the descendants of, older technologies [82,302].

An evolutionary framework also seems the best way to view more general *economic* change, which is hardly surprising given the impact of technological change on economies [296,760]. Although not widely accepted:

> The central point of [Schumpeter's] whole life work [is]: that capitalism can only be understood as an evolutionary process of continuous innovation and "creative destruction" is still not taken into the bosom of mainstream theory, although many now pay lip service to it [383] (page 126).

Douglas North's *Understanding the process of economic change* makes uncertainty and non-ergodicity (i.e. choices made in the past matter for the future) central to the understanding of economic change [773]. While not a grand theory, but a helpful frame within which to view

[12] Schumpeter said later in life 'Destruction may not be the right word after all. Perhaps I should have spoken of transformation' (quoted on page 9 of [914]).

technological and economic change, the evolutionary approach is central to understanding the nature of technological change, its impact, its predictability, and the sorts of interventions that should be made.

Some of the above evolutionary aspects of technological change are well illustrated by the development of computing technology. As is well known, this arose from several motivations, especially the need to decrypt encrypted messages in World War II. Subsequently it has found application in every field, much like a new species colonising a new area, and then leading to a rich variety of descendants [305,742,743]. The progress has been ongoing, but in fits-and-starts (punctuated equilibria) [985]. Its enormous impact was not foreseen at the time of its first development; a pattern that recurs with almost all technologies recognised as disruptive in hindsight – see Chapter 3.

2.4 What is new about new technology?

What is new about anything new? This is the philosophical problem of change:

> All change is change of something. There must be a *thing* that changes; and that thing must remain, while it changes, *identical with itself*. But if, we must ask, it remains identical with itself, how can it ever change? [846] (page 155).

This question is some two and a half thousand years old. Karl Popper quotes the observations of Greek philosopher Parmenides of Elea:

> All change, including qualitative change, is due to spatial movement; more especially, to the movement of unchangeable atoms in the unchangeable void. Thus all change is rearrangement [846].

Technological change can be viewed as the rearrangement of components. This is the Schumpeterian model of entrepreneurship[13] [947] (page 66), 'new combinations of productive means', or as it was put later by Usher

> The quality and importance of great achievements are due to the cumulative synthesis of a very large number of small achievements. These accomplishments are the result of processes of thought and action common to all humanity, and, at a slightly lower level, to the primates [1083] (page 83)[14].

---

[13] The nowadays common distinction between invention, innovation and diffusion is also credited to Schumpeter [822,913].

[14] Viewing technologies as hierarchical arrangements of components explains how it can be that certain elements of technological change seem remarkably well predictable, but other aspects are unquestionably not (see Chapter 3). The prediction of minor changes is conceptually simple – everything else remains the same, and some small component varies; for example, Nickel Metal-Hydride batteries are replaced by Lithium-Ion batteries in mobile phones. But the sorts of technological change that cause large impact that are either sought after or worried about are precisely those that overturn entire systems (for example the replacement of physical stores by online stores), and thinking about such change *in terms of the old technologies* is limiting:

> When drastically new technologies make their appearance, thinking about their eventual impact is severely handicapped by the tendency to think about them in terms of the old technology. It is difficult even to visualize the complete displacement of an old, long-dominant technology, let alone apprehend a new technology as an entire system. Thus, time and again, new technologies have been thought of as mere supplements to offset certain inherent limitations of the old. In the early years, railroads were thought of merely as feeders into the existing canal system, to be constructed in places where the terrain had rendered canals inherently impractical. In precisely the same fashion, the radio was thought by its originators and proponents to have potential applications mainly where wire communication was impractical, for example, ships at sea and remote mountain locations. (The old term 'wireless,' still employed in Britain, effectively perpetuates that early perspective.) The extent to which the old continues to dominate thinking about the

This observation correlates to the point that all technologies comprise particular arrangements of components. Rather than leading to new technology *per se,* technological change leads to new combinations, applications and therefore new uses of technology embodied in new products or processes[15] [403,1119] (Section 1.2). The first commercially available smart phone appearing at the beginning of the 21st century, was marketed as a new technology, even though it was made from existing technologies and was built on generations of earlier products, *and* fulfilled pre-existing functions.

New technologies are thus never entirely new [321,652]. For instance, at the turn of the 19th century, weaving technology changed when the loom became mechanised with the adaptation of punch cards (the Jacquard loom). The punch cards, joined together into a continuous sequence, controlled the weave in the way loom workers did previously. These cards could be regarded as an early analogue form of fixed programming. Almost a hundred years later, punch card technology emerged for a different use, this time for data storage, with Herman Hollerith's patented tabulating machine designed for the 1890 US census. Punch card technology continued to be an important data storage technology for another century before being replaced by magnetic tape as a means of storing data, although it still remains in use in the collection of census data and for some voting machines. Therefore, over 200 years this technology has had a long history of use, re-use, adaptation and use for a purpose which was not originally envisaged [306].

Given that no user can know the inner workings of every technology, the potential of new products can be startling from the outside: gradual incremental change can appear revolutionary even in hindsight. The perception of the newness of a technology stems from the way the technology is imagined, its application and use at any given time. Different people will have different motivations for promoting a given technology as new and disruptive and in turn, people understand and experience the newness of a given technology differently. For instance, a business or industry may wish to promote a given technology as a new innovation with unique applications and uses. In contrast, a group that wishes to oppose the uptake of a new technology may emphasise the uncertainty associated with its use and impact.

The way in which new technology is imagined and understood has implications for the way it is assessed and managed. Emphasis on the newness or disruptiveness of a technology – and the positive or negative reactions associated with these – can hide the history of a technology and adversely influence how technology is imagined, developed, evaluated and regulated.

2.5 Technology as a parts-assembly process

The parts-assembly nature of technology describes how all technologies are built of components or parts[16]. Each part emerges in its own complex system with its own histories and

> new is nicely encapsulated in Thomas Edison's practice of regularly referring to his incandescent lamp as 'the burner.'[597]

One can conclude that ignoring the componentisation of technology, or viewing new technologies in terms of the old, can be limiting to understanding, and thus presumably limiting to their prediction.

[15] Recognising that 'new' technologies are (essentially) new combinations of existing components deals with many Heraclitean anxieties regarding the tension between change and stability [649,943].

[16] Surprisingly this is not widely accepted:

> Today, the literature on innovation does not study innovation as combination. Theoreticians on technological (invention and) innovation, from the very earliest (e.g.: Abbot P. Usher [1083], Colum S. Gilfillan [421], Josef A. Schumpeter, Simon Kuznets [594], Everett M. Rogers [894], Chris Freeman [382]) up to today [36,82] regularly define or rather briefly mention innovation using the idea of combination, but without studying the phenomenon. There is also a research tradition (*technological change*) that defines innovation in terms of a new combination of factors of production. But combination here has no connotation

path dependencies. The ability to make technologies, systems and organisations function together is fundamental to the shaping and changing of technology [517,809].

The degree of interoperability affects how pervasive a technology can become, and its potential economic and social impact. Infrastructure plays an important role here, providing an underpinning layer with which many standardised parts can interoperate whether those parts are railway tracks or computer communication networks [130,325,884,997]. The interoperability of technology products and artefacts can increase efficiencies by lowering costs of switching between tasks/products; afford consumers more choice by limiting the effects of being locked in to any one system; allow free movement of ideas and increase the flow of trade [809].

*M*odularity is the degree to which a system's components may be separated and recombined. It allows the independent design of different parts. Modularity is the key to interoperability, and to the design of any large technological system. Interoperability enables the combinatorial innovation and parts-assembly that is central to the evolution of new technologies [1091]. Many new technologies are almost defined by interoperability, such as peer-to-peer computing [1014]. Interoperability is sometimes in conflict with intellectual property rights as 'strong intellectual property protections work at cross-purposes to interoperability and, thus to innovation' [809].

Standards in turn help modularity and interoperability by setting rules and guidelines to ensure that individual components can work together. For example, the development of converter technology and associated standards allowed adaptation of American television programmes into usable formats for Australian televisions. This significantly increased the variety of entertainment available to Australians [152]. Simple standards that outline specifications and procedures and are made widely available allow for easier combination of individual components. This is nicely illustrated with the diffusion of the compact disc (CD) which resulted from the cooperation of two firms, Sony and Philips, who worked together and openly licensed their CD patents as a means to establish the technology. While the CD was incompatible with existing audio technologies such as the phonograph, cassette players and reel-to-reel tapes, it was not in competition with any other similar 'new' technology at the time.

Standards also manage the risks associated with new technologies, with safety standards arising from the modern safety movement [151,177]. These standards are typically specified levels of performance. For example, the degree of insulation an electrical appliance must have in order to protect the user.

---

at all relating to creativity. It is essentially economic: the substitution of labour and capital in a new way (or combination). In addition, the idea of combination in economics is very frequently associated pejoratively with imitation or a minor (incremental) innovation. Not novel (revolutionary) enough. It is *bricolage*, in Claude Lévi-Strauss's sense [609]: a *bricoleur* combines bits and pieces, remains and remnants of previous activities in a contingent way. ... Over the twentieth century the representation of innovation as a faculty of combination gave way to an economic representation that became dominant and even hegemonic: innovation is the commercialization of an invention, page 15 of [430].

As society changes, so do standards. Changes in technology require changes in standards to ensure interoperability of technologies, but it is not only changes in technology that result in changes to technological standards (e.g. improved signal processing technology allowing greater data transmission speeds over telephone wires necessitated new standards for modem communications). For example, building code standards for door frames were recently increased in the Netherlands to accommodate the increasing height of the average Dutch male (1.8 m). These standards are likely to change again as the average height is expected to reach 1.9 m by 2050 [466].

Box 4: Changing standards for door frames in the Netherlands to accommodate changes in average height

The introduction of standards can be difficult. Standards wars are battles for market dominance between firms seeking to develop incompatible technologies [962]. One of the downsides when standards are widely adopted is the potential to lock-out future technologies which could actually offer better performance and greater interoperability (Section 2.6). A contemporary example is the choice of particular technologies for the National Broadband Network (NBN) [747,1004]. Since the commencement of the NBN project, technological advances have enabled much higher speeds over existing networks, such as cable-TV networks, by using channel bonding (the utilisation of multiple independent physical layer channels) [291,1125]. Locking in the design of a system that will take many years to build means not being able to exploit advances that occur along the way. Adoption of emerging new standards is to be encouraged; any new technology needs to fit into the existing system or create a technology that can facilitate its incorporation.

Different technologies require different levels of compatibility. While a single worldwide standard for fax machines or modems is crucial for compatibility, multiple formats persist for cellular telephones and digital televisions, where compatibility across regions is less important. Having simple, flexible and open standards ensures compatibility and interoperability of technology components originating from different disciplines, companies and industries. An example is the Internet Protocol Suite TCP/IP, designed with bare minimum requirements to allow access to all types of hardware and software. As a result, the suite has been implemented on essentially every computing platform. Standards are a form of intervention that both industry players and governments can use to support modularity and interoperability facilitating the adoption of new technologies (Section 7.7).

2.6 Choice, combination and diffusion

Many choices are made in the development and adoption of a technology or product. And the longevity of the technology or product depends on decisions made after adoption [894]. The choices made by actors at all points of the innovation process influence future options. For example, choices surrounding autonomous vehicle technology uptake include: identifying a social problem (public awareness of human and environmental harm from personal motor vehicle use); R&D (available funding and research skills, technology advance, open access to knowledge, regulation, standards, laws, infrastructure); commercialisation (economies of scale, design improvement); and adoption and diffusion (attitudes to autonomous vehicles, changing business models), see Appendix C.3 [931]. The emergence, adoption and diffusion of autonomous vehicle technology will depend on decisions made at each phase of the innovation process. These do not proceed in a linear fashion according to a set of distinct and chronological steps. They are interlinked and interdependent, with many feedback and feed-forward mechanisms [894].

Technological change does not only occur when a given technology changes in performance, efficiency or cost. The creation of Electronic Funds Transfer at Point of Sale (EFTPOS) – an IT network set up by British retail banks and later adopted internationally – illustrates how combining minimal change to an existing technology with significant change to various elements of the technology complex, can lead to widespread diffusion. Box 5 contains a sample of some of the complex choices made by the banking industry in the adoption of the EFTPOS system.

Material/artefact Variety in the designs of computer, software, communications and terminals imposed an expertise management problem on the banks. Isolated artefact design decisions had unexpected implications for other network component design and cost.

Topology/layout The artefact components could be linked in different ways to represent preferences of the owning organisations. So transaction processing could take place in a jointly owned organisation, or the banks' IT departments. Terminals could be stand-alone or integrated into retailer equipment. Such decisions had implications for competition, ownership and control of the network, and changed through the project.

Procedures/software There were many ways of building security into the network. One possibility was to encrypt electronic messages, but the two rival proposals for encryption method each had their own political and competitive implications.

Organisational structure and location of technical expertise – knowledge/skills The banks had to decide how to organise the development of the network. They first experimented with the option to contract out responsibility for network design, then a jointly owned hybrid organisation of technical consultants controlled by commercial bankers, then full-scale development which occurred through VISA and Switch network designs, which each bank made an individual decision to affiliate with.

Cost/capital The cost of IT networks is large, and returns depend on the speed with which paper-based systems can be closed down. There is a theoretic role here for sophisticated financial evaluation techniques, but the impetus for the technology derived from inter-bank competition rather than the immediate economics.

Industry structure As an oligopoly, the banking industry had a range of more or less cooperative or competitive options available for this large-scale project. The banks began by cooperating fully in their approach to EFTPOS, but cooperation broke down, and two factions developed rival designs of a/the network.

Social/legal relations In 1986 the UK government passed legislation that allowed building societies to compete with banks. This helped prompt the breakdown of the banks' cooperative approach to network design.

Culture Past experience of government led many of the banks to expect the Bank of England to regulate the sector and to signal its approval or disapproval of bank strategies. On the EFTPOS project some banks continued to wait for Bank of England guidance, some interpreted Bank of England statements as signalling approval or disapproval; late in the project most banks agreed there was no longer the close supervision of earlier years

Box 5: EFTPOS technology as an example of a technology artefact adoption. Source [364], reproduced in [504].

During the early stages of diffusion, EFTPOS was described as a new technology because cash, cheques and credit were the methods of choice for the transfer of money at the time. It is perhaps more accurate to describe EFTPOS as a new combination of existing technology which allowed a new application – the electronic transfer of funds. Initially, consumers and merchants were slow to accept EFTPOS, and marketing was minimal. Interoperable systems, standards and networks had to emerge before institutions such as banks, industries and shops could adopt this kind of fund transfer system. EFTPOS has now become a standard payment method across most of the globe [364,504].

There is no single causal chain or tipping point in the diffusion and adoption of technologies. The progress of any technology will depend on the progress of its individual components which in turn each rely on a web of technical, social and economic influences, often depending crucially on serendipitous combinations [382,683,1005].

As a technology changes, a component may obstruct change or innovation (described as the reverse salient [508]). A reverse salient can impede progress or it can act as a tipping point for further innovation. Overcoming the reverse salient in a technology system will typically bring another problem to the forefront. Widely used technologies like the internet can facilitate an open approach to resolve reverse salients. The open source software movement, for instance, allows a multitude of coders to identify and correct reverse salients in complex software programs [164].

2.7 Lock-in and technological inertia

The web of connections emerging from and sustaining a widely distributed technology is described as a 'socio-technical complex' [653]. A socio-technical complex or system consists of manufacturers, developers, businesses, industry and users, and includes cultures of manufacture, regulation, and the networked and interlinked technologies and infrastructure. The histories, sunk costs and vested interests which exist in the interdependent systems can either enable or prevent the diffusion of emerging technology [403,823,826,944]. As an entire system becomes locked in, it becomes increasingly difficult to effect change, even when there would be clear benefits from change[17].

Technological change depends on a conducive socio-technical environment. A high level of resistance can obstruct the adoption of new ideas or technologies or it can discourage their emergence altogether, this is described as technological inertia [706]. Technological inertia can result from vested interests which seek to maintain the status-quo, including businesses that believe their existing business model or work practices are threatened by new technology, called the 'innovators dilemma' [183].

Resistance to technology change can stem from a number of different sources and mechanisms. Technology change may disadvantage some, for example a worker may lose their job or face changes in their work environment (Section 4.3.5). Or technology change may threaten the world view or cultural identity of a person or group (Section 5.1). On introduction into the market, a new technology may not be supported by the right tools, materials or skills, or its adoption may depend on its interoperability with other components. In many cases, the rate of adoption depends on the number of users, which can also affect economies of scale [708].

Technological inertia and lock-in can occur at many different points throughout any socio-technical complex (Box 6). Company level lock-in can result from the interdependence of industries as they begin to rely on each other – creating design-specific standards and demand-supply relationships with each other. Incumbent companies can also be tempted to shift their focus from product innovation to process innovation. This know-how becomes the basis of the company's competitive advantage and its identity, which helps to preserve the status-quo and increase the chances of company lock-in [1056,1076]. This inertia is a property of the *system* and is not always due to deliberate agency. Thomas Hughes instead describes it as 'technological momentum', which is sometimes mistaken for autonomy in the sense that the technology has a life of its own beyond our control[18].

---

[17] Joel Mokyr coined the phrase 'Cardwell's law' to describe the historical pattern that in most societies when there has been technological innovation, eventually conservative forces grab power and bring innovation (and hence economic growth) to an end [707]. As Lilley put it 67 years ago [617] (page 189:):

> The form of society has a great effect on the rate of inventions and a form of society which in its young days encourages technical progress can, as a result of the very inventions in engenders, eventually come to retard further progress until a new social structure replaces it.

[18] Hughes explains the momentum as arising as follows:

> Technological systems, even after prolonged growth and consolidation, do not become autonomous; they acquire momentum. They have a mass of technical and organizational components; they possess direction,

The development and diffusion of the urban sanitation system illustrates how a socio-technical system emerges from a web of social, cultural, democratic, security, economic, and technical phenomena. Its emergence relied on technical innovation as well as change in practices. In Sydney in 1844, sanitation systems were only available to those who could afford to connect to piped water. The contemporary meaning and practices surrounding sanitation were changing as physical well-being and a clean environment became associated with social progress. Any attempt to shift toward more sustainable alternatives now will need to consider the resulted changes in technology, culture, society, regulation and institutions over a prolonged period of time broader environment and social contexts [346].

Box 6: The emergence of urban sanitation in Sydney

Once a market is established, institutions such as technical and professional associations often emerge as gatekeepers between end users and professionals. Voluntary associations such as social automobile clubs, unions, industry associations or media channels such as magazines or electronic social media sites can act as non-market (i.e. social, cultural or governance) forces of lock-in. Emergent technologies can also create brand new academic disciplines which are then absorbed into research and teaching institutions. Social norms play a part in lock-in when people can become locked in to new social practices associated with the uses of technologies. For example, the use of personal automobiles has shaped the way people live and work including their leisure time, and the development of electricity networks has shaped home-making and leisure [1076].

Powerful vested interests fight to maintain the status quo. Technological change can result in substantial losses to regions, states, firms, industries, agencies or individuals who are heavily invested in a widely used and market-dominant technology. Loss can be defined in financial terms but can also include knowledge, skills, power and reputation. Vested interest can be responsible for the lock-out of new products and businesses. Vested interest does not only come from business and industry, it can exist in community groups, research, politics and government. Existing industries and structures can wittingly or unwittingly obstruct new entrants into the market, through structural, legal and political forces [708].

Lock-in created by technological inertia and vested interests means that a substantial technical performance improvement is often needed in order to induce a transition from a widely adopted technology to a new technology. Such substantial improvements often come from niche and entrepreneurial entrants to the market. To achieve structural change, policy must support the growth of new technologies and industries [700]. Legislation can help to create niche markets, and if there is variety in the niche markets created then technical advances are more to likely occur [215]

'Gateway' technologies can act as a bridge between two incompatible technologies and can be useful in overcoming lock-in [239,246,247]. For example the DC–AC power inverter changes direct current electricity to alternating current electricity. The inverter can convert direct current electricity from a battery or solar photovoltaic panel to alternating current electricity which can be fed into the electricity grid [708]. Or the use of virtual-machines [974] and related technologies [290] in computer systems which allow one computer system to emulate another, or allow multiple software components to interoperate [689]. Gateway technologies can reduce

or goals; and they display a rate of growth suggesting velocity. A high level of momentum often causes observers to assume that a technological system has become autonomous. Mature systems have a quality that is analogous, therefore, to inertia of motion. The large mass of a technological system arises especially from the organizations and people committed by various interests to the system. … Momentum does not contradict the doctrine of social construction of technology, and it does not support the erroneous belief in technological determinism. The metaphor encompasses both structural factors and contingent events [508] (pages 76 and 80.).

the systemic resistance new technologies face and solve what seem to be intractable incompatibilities between differing standards [470,708].

Because of the numerous and complex variables in the broader socio-technical complex, any transitions require change in technology, government, and legal and regulatory structures which can take decades to achieve [1077]. Each example is different and complex [403-405,1065], but can all be understood from an evolutionary perspective (Section 2.3) as 'evolutionary reconfiguration' [402].

2.8 'Transformative' and 'disruptive' technologies

As earlier sections have described, technology results from a process of parts assembly and new technology emerges from a combination of pre-existing technology or knowledge. The many uncertainties and multiple possibilities inherent in technology change can lead to the perception that technology appears out of nowhere and has transformative and disruptive properties. The perception of technological change as gradual or sudden depends upon the time-scale examined, and whether one is aware of the antecedent technologies. For example, if one is unaware of the progress in packet-switched computer networks starting in the early 1960s, it may be surprising to see the (apparently) sudden appearance of the world-wide web in the 1990s. Some technological changes are more rapid or of larger magnitude than others. This leads to the idea that there is some intrinsic difference between gradual and sudden change, and between 'incremental' and 'radical' technological innovations[19].

New technology may be seen as disruptive (usually in hindsight), depending on the context of use and the motivations of those involved in its diffusion. Even technology that is understood as new and appears to have a sudden and marked impact is constructed from ancestor technologies and processes. Radar is often described as a disruptive technology of the 20th century. Brian Arthur [35,1021] argued that *radical* innovations (the ones that have large and surprising effects) are intrinsically different, and not explained by an evolutionary model which

> does not hold up for what interests us here: radical invention by deliberate human design. Radar certainly did not emerge from the random variation of 1930s radio circuits [35,1021].

In fact radar did emerge in this way, as is documented in histories of the technology [750,1021,1126]. It was first demonstrated in 1904 by Christian Hülsmeyer and its performance gradually improved through multiple small variations. Its wider deployment was particularly enabled by the development of a component technology, the magnetron. The magnetron was crucial to the improvement of radar performance to a level where it could be widely used. But radar as a technology itself, had a gradual evolution. Furthermore the magnetron itself can be seen as one of many steps in the gradual evolution of vacuum tube devices [125].

---

[19] The words 'incremental' and 'radical' convey many different meanings. The common distinction is exemplified in [1045], which distinguishes between the two types in terms of market-pull versus technology push (Section 2.2)

> *Radical innovation* leads to fundamental re-orientation of patterns of business, the creation of new industries, products or markets, technological advances that significantly affect scale and change the fundamental competitiveness of technologies. Over time, radical innovation shifts processes and opens up new markets and product applications. … *Incremental innovation*, in contrast, is driven more by market-pull than technology-push. Incremental innovation enables businesses to compete successfully by developing new products and/or services built on their existing expertise.

Norman and Verganti use the two terms to distinguish between innovations that don't (or do) change the *meaning* of some technology (in the sense of Chapter 4); this is a valid distinction to make, but it is independent of time-scale and apparent slopes of change curves. The confusion between these concepts is illustrated in the correspondence regarding their paper [772].

Radar was invented more than once; Jantsch claims 'Radar literally had to be invented twice' [531] (pages 69-70). Such multiple invention is in fact the norm in science [680] and technology [1108]. As Gilfillan said: 'Simultaneous duplicate invention often occurs, and constantly would occur if not forestalled by news that the invention is made' [420] (page 32). In fact, reinvention occurs regularly in all innovative activities [885].

The radar example illustrates the value of the evolutionary perspective (Section 2.3): recombination and gradual variations eventually leading to a large impact, multiple independent inventions, and seemingly radical inventions that appear more gradual when examined more closely. The disruptiveness of a technology is not an intrinsic attribute of the technology; it is a function of the environment which the technology is disrupting (Section 4.1).

Given the prevalence of the 'disruptive' technology concept, three more examples are presented that have their own case study – 3D printing (Appendix C.1), autonomous vehicles (Appendix C.3) and massive open online courses, or MOOCs (Appendix C.8) are widely cited as potentially disruptive technologies – the reports show how a diverse range of issues that exist in each broader system make it extremely difficult to predict when and how a technology will make an impact. The impact from 3D printing is expected to arise from the shift in design and manufacture of goods from small and medium-sized businesses, community hubs and individuals; the autonomous vehicle has for many decades been anticipated as a solution to reducing car accidents, traffic congestion and pollution; and MOOCs have been cited as an emerging technology platform that is driving a rapid revolution in tertiary education. This section examines a broad range of factors involved in their development and widespread diffusion to gain a better understanding of their revolutionary potential.

3-D Printing

The current applications of 3D printing technologies are a result of changes and modifications of pre-existing printing technology and developments in other components. 3D printing technology can be considered a collective term for a recent and emerging version of a set of related technologies that have been used in large-scale manufacturing for more than two decades [1142]. 3D printing has raised concerns about intellectual property and regulation. Users will infringe copyright, patents and design rights by producing unauthorised objects. The 3D printed handgun raises issues about the misuse of decentralised and unregulated manufacturing. Widespread diffusion of 3D printing will depend on internet connections, speeds and access to online resources. These are important issues to resolve if Australia wishes to support the ubiquitous use of 3D printing technology. However, just because this type of manufacturing can be done in the home, does not mean it will be adopted widely. 3D printing currently requires good ideas, design skills, software, computer skills and materials. People will need the skills and motivation to adopt this practice in their home. It is more likely that in the short term Australians will see an increase in local 3D printing stores and community hubs such as FabLabs (see Appendix C.1, [541]).

Autonomous vehicles

The use of the collective term 'autonomous vehicle' can hide the multitude of individual technology components that are required for its successful development and use. Because each technology component – sensors, data processing, mechanical control systems, communications and networking technologies, for example – will develop at different rates (due to their own complex socio-technical systems), the development and adoption of each component and therefore the adoption of autonomous vehicles become very difficult to predict (Chapter 3). In addition a fully autonomous vehicle system requires building smart transport infrastructure. Even if (or when) these technical challenges are overcome and the vehicles become affordable, the meanings people give to their cars and the cultures and practices of driving still need to be considered in shifting driving responsibility from human drivers to computers. In the current environment, increasing levels of autonomy in the car can be managed within existing legal and regulatory frameworks, but this may not be so straightforward if there is a transition to higher levels of autonomy (in for example a fully driverless car). Removing responsibility and accountability from human drivers will challenge many existing laws and regulations and change liability laws, particularly for car manufacturers and insurers (see Appendix C.3 [931]).

MOOCs

It is unlikely that any single platform such as MOOCs will single-handedly completely transform a complex system such as tertiary education; there is no 'avalanche coming' [74]. Gaining access to information and becoming accredited in a program are only some of the benefits associated with attending university. For some students in-class and hands-on experience or social and networking prospects of university life are equally important. MOOCs offer courses (not degree programs) and they depend on the existence of reputable universities, which provide trust, status and therefore value to the student. The perception of MOOCs as revolutionary has shifted following initial widespread and often uncritical enthusiasm, and education leaders now discuss the drawbacks of MOOCs in tertiary education. In some cases, MOOCs have developed into small private online courses. These combine online resources and technology with personal engagement between staff and students to provide in-classroom teaching to significantly smaller numbers of students than MOOCs. Early research indicates that fostering a valuable classroom experience with smaller numbers may improve higher education using online courses (see Appendix C.8 and [391,764,795,796,819]).). For all the talk (and worry) about their potential radical disruption of higher education, when compared to more creative efforts to imagine a radical but feasible future [994], MOOCs alone seem very ordinary. This illustrates the difference between starting with a technology and attempting to predict its impacts, versus starting with a problem and working back to see what is need to solve it (including technology) – see the discussion in Section 3.6.2.

New technology develops within an existing ecology of things, people, cultures and contexts. There is no single tipping point for the development or diffusion of any given technology. The diffusion of any technological change is usually gradual and heterogeneous, even for those technologies that are expected to be transformative and disruptive. The adoption of new technology and its diffusion depend on many technical and social factors in the broader socio-technical environment.

2.9 Uncertainty and Australia's capacity to adapt to technological change

Technological change is an intrinsically uncertain process. Nations have differing capabilities to adapt to it, and skills underpin this difference. This section will examine the inherent uncertainty in technological change and how Australia can improve its response to technological change.

2.9.1 Uncertainty and failure are integral to technological change

Technological innovation and progress result from trial and error, mistakes and unexpected successes [986]. All technology is developed and improved by trial and error: no new technology product or artefact is perfect. Technologies are improved on, fall in and out of favour, and specific products or processes cease to be used. Australia's capacity to adopt emerging technology will also depend on the approach of its citizens, governments, industries and businesses to uncertainty and failure.

Innovation is about experimentation. The entry, exit and failure of firms is a normal part of the economy and occurs in all industries [302]. The observed lifetime and number of specifically technology-producing industries confirm that failure is an integral part of technological change, no matter what the technology product or industry (Figure 5).

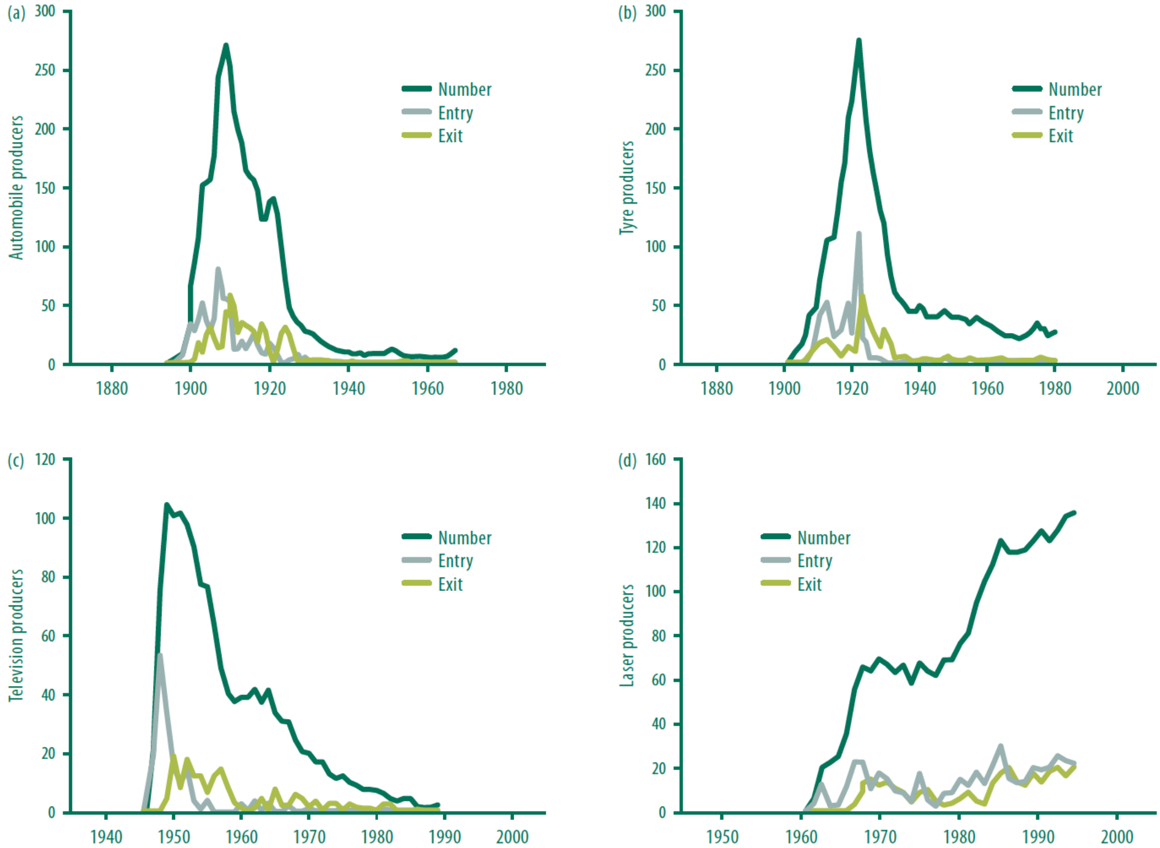


Figure 5: Entry, exit, and number (a) of automobile producers, 1985-1996; (b) of tyre producers, 1901–80, (c) television producers, 1946–89; (d) of laser producers, 1961-94. Sourced from [33,302].

In Australia, of the 299,123 new business entered the market during 2008–09, by June 2010 there were 75.8% still operating, and by June 2012 only 51.0% were still operating [6].

If innovation and progress are key to business success, then uncertainty and failure must be accepted as their unavoidable consequences. A cultural appetite for risk and change which acknowledges the important role of failure will facilitate the benefits of technology change. Despite popular Australian narratives, there is no clear evidence that Australians are less entrepreneurial and risk-taking than citizens of equivalent OECD countries [79,897,898]. In fact it is difficult to find reliable international comparisons on cultural aspects that might encourage the people of a nation to be more innovative and risk-seeking. Geert Hofstede developed the most widely cited theory of cultural dimensions[20] in an attempt to measure how innovative a group or nation can be [497]. Although Hofstede's dimensions have been subject to criticism they are still the most commonly used for cross-country comparison. Using these cultural dimensions studies have shown low adoption rates of ICT have been found in countries with high power distance (i.e. inequality of power distribution and centralised decision structures)

[20] Hofstede's cultural dimensions include: power distance (the degree of inequality that exists among people with and without power); individualism/collectivism (the strength of the ties people have to others within the community); masculinity/femininity (how much a society sticks with, and values, 'male' and 'female' roles); uncertainty avoidance (the degree of anxiety that people feel in uncertain or unknown situations, the level of rules and order as opposed to a society that enjoys novel events and values differences); and long-term orientation (the degree to which time-honoured traditions and norms are maintained while viewing change with suspicion)[337,1001].

and high uncertainty avoidance (i.e. degree to which individuals feel comfortable with uncertainty and risk) [337]. However, cross-country comparisons are particularly difficult given the complexity of contemporary global cultures, and the cultural, social, and politic dynamics of regions. There are large differences in characteristics such as wealth, open debate, independence of media and levels of industrialisation making comparative interpretation of findings in cultural attitude studies very difficult.

Although cultural dimensions are difficult to define, measure and compare, there is value in understanding the role cultural forces play in technology adoption. Culture, meaning and identity – at the individual, group and national level – inform how risk is assessed and people behave (Section 5.2.4). The degree to which people, businesses and governments are comfortable with risk-taking and uncertainty will affect their ability to cope with technological change.

2.9.2 Australia's capacity to adopt emerging technology

The global technology revolution 2020, a report released by the RAND Corporation, found that Australia has an excellent capacity to acquire a broad range of technologies [970]. The report assessed 29 countries on their capacity to adopt selected emerging technologies to promote economic and social progress, ranking Australia as having the capacity to acquire all 16 of the report's chosen technologies [1144]. The RAND report describes the levers of technology adoption available to a nation. Box 7 indicates whether those levers are considered drivers of technology adoption or barriers to it – or both – in Australia.

Drivers and barriers to technology adoption for Australia

	Driver	Barrier
Cost and financing	x	
Laws and policies	x	x
Social values, public opinion, and politics	x	x
Infrastructure	x	
Privacy concerns	x	x
Use of resources and environmental health	x	
R&D investment	x	
Skills, education and literacy		x
Governance and political stability	x	

The above drivers and barriers were identified for the following 16 selected technologies cheap solar energy, rural wireless communications, GM crops, filters and catalysts, cheap autonomous housing, rapid bioassays, green manufacturing, ubiquitous radiofrequency identification tagging, hybrid vehicles, targeted drug delivery, improved diagnostic and surgical methods, quantum cryptography, ubiquitous information access, pervasive sensors, tissue engineering and wearable computers [1144].

Box 7: Levers of technology adoption can be drivers or barriers, depending on context. Levers are annotated as drivers of (D) or barriers to (B) technology adoption in Australia. Sourced from [1144].

There are many factors that further influence the uptake of new technology by business and industry. Australian businesses report that most of the new goods and services adopted are new to their business only (75%), compared to an innovation that is new to Australian industry (9%), new to Australia (8%) or new to the world (11%) [7]. New – to individuals, businesses and other institutions can often mean the technology is new at the point of adoption, not a new invention.

Estimating the degree to which any technology is adopted across different businesses and industries in Australia is difficult due to the complex and multidimensional nature of technological change. There is no one-size fits all approach to encourage technology adoption. From one business to another there can be a large difference in available resources, skills, strategy, motivation, culture, organisational structure, environmental and local issues. A report examining the adoption of automation technology in the Australian resource industries, for instance, found that due to immense variety across the many operations that compose the industries, the degree of uptake of automation was extremely difficult to predict [56] (see Section 3.4).

The SAF05 project has identified a range of factors important to the uptake of technology by Australian business and industry, Table 1.

Factor	Mechanisms that can influence technology uptake
Cost	• Compliance burdens of regulation • Programs for capital de-risking e.g. The US Small Business Innovation Research Program encourages domestic small businesses to engage in government-supported R&D that has the potential for commercialisation • Tariff barriers and differential pricing by multinationals
Policies, regulations and laws	• Focus on the desired goal rather than picking a technology winner e.g. set policy to decrease carbon emissions, allowing innovative solutions to emerge. • Policy stability will encourage long-term investment in most industries. • Be open to exploring a range of options, encouraging a 'fail fast' culture of a rolling series of pilots and experiments • Ensure that patent systems do not act as a brake to innovation. • Most issues around new uses of technology can be addressed by common law and do not require technology-specific laws. • Design regulations and laws should focus on outcomes i.e. regulate for the effect of technology, not the technology itself.
Collaboration	• Collaboration between research, university, business and industry sectors is crucial to solving major problems and creating a highly skilled workforce. • Innovation policies should be designed around the problem, rather than existing industry sectors or technologies which may put barriers in the way of inter-industry collaboration. • Encourage existing institutions such as universities to free up their IP arrangements to enable the IP to be more freely used.
Open data	• Ensure data that is owned by the government, or that the government is a custodian of, is made freely available and shared by default.
Privacy and security	• Impediments to adopting wireless and cloud technologies in many businesses include security and privacy concerns. This is particularly important in industries such as healthcare where high security standards need to be achieved to ensure patient confidentially.
Standards and interoperability	• Develop and adopt simple, interoperable and (where possible) global standards. Ensure that infrastructure has future flexibility as well as current optimality. • Gateway technologies can act as a bridge between two incompatible technologies and can be useful to overcome lock-in for large and well established systems (e.g. such as energy, transport or ICT infrastructure).
Australian Government as a major purchaser of new technologies	• Recognising the technological aspect of mandated assistive and disability schemes and using this as an opportunity to encourage technological progress. • Implement programs such as the US Small Business Innovation Research Program which shares some of the early stage technological risk.

Attitudes to changing technology and practices	• Model best practice in organisational and workforce change, taking into consideration how new technology will require new roles, work patterns, modes of communication, reward systems, leadership models and workplace training. • Mitigate against negative attitudes to new technology in general by ensuring that there are effective retraining schemes and social safety nets for affected workers.
Approach to risk and failure	• Through education, vocational training and lifelong learning, develop a business/industry/national culture that accepts the uncertainty and failure inherent in innovation. Train people to experiment, and how to learn from (and benefit from) failure. • Recognise there is also risk in maintaining status quo, and not adopting new technologies. • Experiment with multiple technological options for a given problem, recognising that it is unlikely there is only one solution.
Public awareness	• Public awareness of enabling technologies and democratic engagement with the wider community are useful in gaining social acceptance of new technologies. Adoption is promoted through awareness and understanding of technologies and education and skills training. • Targeted communications are required to meet the needs and concerns of varied audiences. Engaging local (affected) groups in the decision making process can facilitate social acceptance. This has been effective in the case of the introduction of wind farms in some areas of Australia.
Skills	• Recognise advanced skills are needed to make use of a new technology effectively, as well as for its invention and creation. • Influence training and education schemes to encourage flexibility, creativity and the ability to try new things. • Minimise constraints on worker mobility e.g. stringent visa rules. • Ensure training content is sufficiently generic to enable workers to adapt to the evolving job requirements imposed by new technologies, rather than highly specific content that is focused on existing technologies employed in past and present jobs.

Table 1: Factors affecting technology uptake by Australian businesses and industries[21]

2.9.3 Skills are needed to deal with change

Skills are needed to develop new technologies. However, even adopting technology developed elsewhere requires the right skills – in a detailed study of technology adoption across 20 countries 'the most important determinants of the speed at which a country adopts technologies are the country's human capital endowment, type of government, degree of openness to trade, and adoption of predecessor technologies' [198].

The boundaries between invention, adaptation and adoption of technology are blurred [922]. People require knowledge and skills to use technology every day in practices such as cooking, or driving, or using a computer or smartphone. In addition, people are faced with problems related to the environment, energy, health and digital technologies and a better understanding of basic scientific knowledge and quantitative skills can help people to deal with these issues [648]. Preparing students in science, technology, engineering and mathematics (STEM) courses will improve their understanding of basic scientific and technological knowledge which may develop citizens who have the confidence to engage in open and democratic discussion about Australia's technological future.

[21] Reports that informed the list of factors affecting uptake of new technologies by Australian business and industry include [49,56,155,209,264,286,308,463,476,647,1142].

> Earlier economic transformations were associated with a major public investment in infrastructure: canals, railroads, electric lines, and highways. The transformation taking place today seems to require an entirely different kind of public involvement. An educated population is the most critical infrastructure of the emerging economy. It is critical for both the economic growth of the Nation as whole, and the success of individuals acting as either consumers or employees [1078].

While economists have long recognised the significance of education in improving adaptability to emerging technologies, what is missing is empirical evidence on the best *type* of education and training to facilitate faster adoption of emerging technologies. Disentangling the roles of education and experience is problematic [1118]. Developing problem solving capabilities and adaptive capacity in Australian workforces is likely to improve the capacity for businesses to adapt to technological change.

Vocational training, in particular, must achieve a better balance 'between the "generalist" qualifications of secondary and higher education and the job-specific competencies currently delivered by the VET system' [1121]. Specifically it has been suggested that vocational training in future should focus more on 'vocations' or 'vocational streams', which represent groupings of similar occupations rather than the present focus on competencies that are highly specific to tightly defined job qualifications[22]. The intention is that education and training to develop workers' 'vocational capabilities' should provide a better balance of skills so that workers are able to perform their current duties with existing technologies and also to adapt to emerging technologies with the confidence to modify and improve processes and practices in the future.

Fast adaptation will continue to provide competitive advantage [299,303,705]. Australia needs a workforce that is able to innovate and adapt in an environment of uncertainty and change.

While the knowledge to use and change technology can be codified to a certain extent through written or verbal methods and training (e.g. books, operating manuals, verbal instructions), attaining and using some knowledge necessitates other forms of learning that cannot be easily provided by external training. This is known as tacit knowledge. For instance, a medical student requires a significant amount of tacit knowledge when using X-ray data in the diagnosis of pulmonary disease.

> At first the student is completely puzzled. All he or she can see in the X-ray photographs of a chest is the "shadows of the heart and the ribs, with a few spidery blotches between them." But after seeing pictures from many different patients, the student will "forget about the ribs and begin to see the lungs." Eventually, a rich panorama of significant detail is observed. Some people would say at this point that they have "got their eye in [805,838].

This type of knowledge is linked to practice and highlights the importance of experience. Learning-by-doing is one way of gaining knowledge – the practice and minor improvements of an activity increase efficiency and therefore productivity. The concept of learning-by-doing is nicely illustrated with the activity of 'finding the biting point' in the simultaneous use of the clutch and accelerator in a manual transmission vehicle. A factory that increases output by learning how to improve the use of equipment without adding workers or investing significant amounts of capital is also using a form of learning-by-doing. Learning-by-doing has been used to explain effects of innovation and technical change, and as an engine for long run growth through increasing returns. Kaizen (meaning 'good change' in Japanese), is the Toyota Production System that has been implemented across many industries, explicitly built upon learning-by-doing to improve standardised activities and prevent waste [746].

---

[22] In this regard it might be noted that in 2013 only one third of VET graduates were in jobs directly associated with their qualification, further underlining the value of training to develop peoples' adaptive capacity.

The ongoing nature of technological change means the workforce requires continual training [625] and thus 'life-long learning' to deal with a changing environment. Educational approaches such as problem-based learning demonstrate an improvement in the ability of people to continue to learn after they have left the formal education system [966,1145]. Problem-based learning, introduced in medical education in North America several decades ago [128], seems an effective way to produce the main skills needed for dealing well with technological change: adaptability; creativity and innovation; empathy; identification of opportunities in a given context; and mental flexibility [625]. The development of these skills in the Australian workforce must be supported by policies that invest in a culture of experimentation, tinkering, an acceptance of uncertainty and an understanding that failure is inherent in technology change (Sections 5.3.3, 7.3, 7.4). Of course, only a small proportion of life is spent at school so it is important to instil skills of lifelong learning. Australian workers need the confidence and ability to adopt emerging technologies and processes that will improve efficiencies and productivity [97].

2.10 Adapting to how technology changes

Technological change, the invention, innovation and diffusion of technology, is a major source of economic growth and social change. Technological change can result from improvements in existing technology, or finding new uses and applications for existing technology, or combining existing ideas, components and processes in new ways. Technology changes through the flow of ideas, knowledge, people, components and processes mean that innovation often comes from the outside.

The disruptiveness of a technology is not an intrinsic attribute of the technology; it is a function of the environment in which the technology is having an impact. The ways in which people understand a technology to be 'new' is shaped by the ways the technology is imagined and by its use at any given time. The uncertainties inherent in technological change can lead to the perception that technology appears overnight and has transformative and disruptive properties.

Technology is a parts-assembly process; it is built from many different parts or components. Policies and simple standards that facilitate the easy assembly of technology components are likely to accelerate the development adoption of technology. Effective policy and decision-making should be based on the understanding that technology, economy and society are interlinked and shape one another. The complexity and interdependence of technological change means there is no single tipping point or simple linear formula for the emergence and diffusion of technology. Technological change does not occur simply because a technology changes in performance, efficiency or cost. There are a multitude of interlinked factors in the broader technology complex that all need to come together in the right way. The ability to make technologies, systems and organisations function together (interoperability) is fundamental to directing and responding to technology change.

To allow new technologies to develop and diffuse, policies and regulations must support the growth of niche markets and entrepreneurial entrants, not only those already in the dominant markets. Once a technology overcomes all the barriers to widespread diffusion, a complex web can develop between all actors in the system – manufacturers, developers, businesses, regulators, industry and users. Resulting technological inertia can impede the introduction of new technologies even when there are clear benefits.

There is no one-size-fits-all formula for technology adoption in business and industry, it is crucial to acknowledge that from one business to another there can be large differences in resources, skills, strategy, culture and organisational structure. The design of industry policies and programs must take into account the different technologies adopted in each business and industry sector, and the motivation and purpose for their adoption.

The Australian workforce must be supported by policies that encourage an acceptance of uncertainty, an understanding that failure is inherent in technology change and a culture of experimentation and adaptation. Innovation and technological progress result from a process of trial and error, mistakes and unexpected successes. The degree to which people, businesses and governments are comfortable with uncertainty, risk-taking and failure will affect their ability to cope with technological change.

Many of these points are reprised in Chapter 7 when interventions are considered – what can a government do to enhance the requisite skill development, encourage the appropriate risk taking, and facilitate an experimental approach?

The evolutionary approach to how technology changes underpins the essence of the next chapter on the prediction of future technologies.

3 Prediction of future technologies

Summary

It is difficult to accurately predict the future evolution, impacts and uses of particular technologies.

It is possible to predict in general terms, the classes of societal problems that are likely to be technologically solved.

Technological prediction in its many forms (e.g. forecasts, scenarios and science fiction) can serve to inspire ideas and creations for the future.

Experts are typically no better at predicting long term technological futures than anyone else.

Technology is made up of many parts, each part with its own history and interdependencies. This means the accurate prediction of a new technology may require accurate prediction of a large number of separate parts. This is hard to do.

Better predictions can be made by learning from the past, predicting solutions of problems instead of future technologies, and using predictions to inspire invention.

Some predictions regarding future technologies are possible. For instance, current general purpose technologies will continue to have wide impact and technologies for data [306] will likely have a large impact across all aspects of Australian life in the next decade.

There are general patterns of technological change that can be expected to recur, and these patterns can inform policy.

It is easy to find fundamental inventions in embryonic state today, dawdling in unpaid obscurity, and to predict a great future for them decades, even a century before it arrives. But it is hard to foresee how much they will be improved by what date, and whether they, or some functional rivals, will be the chief winners in the race towards perfection and popularity.

Seabury Collum Gilfillan, 1952[422]

Over the past year, with the turn of the new century – and Millennium – the media have been filled with speculations. You might call it the 'Where is technology taking us?' syndrome. I want to assert in the strongest possible terms what I regard as the only possible serious answer to that momentous question: We don't know. In fact, I believe that we can't know.

Nathan Rosenberg, 2001[23]

A perfect understanding of the processes that lead to changing technology would allow precise and accurate anticipation and planning of future technological artefacts and processes. Since no

---

[23] Rosenberg goes on later to say

> 'My general point here is that major innovations typically come into the world in a very primitive condition. This primitive initial performance capability in their earliest stages usually renders forecasting extremely difficult. The hard truth is that we can know very little about what the eventual impact of a new technology may be, even after it has proven to be workable. Those future uses can be teased out of the innovation, quite typically only after years or decades of development activity, long after the Schumpeterian entrepreneur has done his work (the D of R&D)' [911].

such understanding can exist, the future of technology is uncertain. This uncertainty invites the prediction of emerging technologies (Section 2.2, 2.9.1).

Predictions are made to reduce uncertainty and surprise, and to exploit competitive advantage. Businesses seek to predict as an aid to investment decisions, particularly longer-term investment. The responsibility to provide for future generations inspires prediction in the hope that by predicting the future people might avoid harmful actions [656]. Governments may wish to predict to implement interventions or to respond to them (Chapter 7). For example, new regulations may be formulated and implemented in response to an anticipated widespread use of driverless vehicles (Appendix C.3 [931]); the potential security threats enabled by new technologies; workforce implications of new technologies (Appendix C.7 [200,868,1079]); educational strategies for future technologies (Appendix C.8 [764]), [55,435,919]; skills and training (Sections 2.9.3, 7.3, 7.4); or the potential infrastructure investments necessary as a result of technological change elsewhere (such as the National Broadband Network); or a prediction may be deliberately made to inspire an outcome (Section 3.3.1).

This report does not make specific narrow predictions of future technologies and their particular impacts (see the working paper *Future Technologies Overview* [343]). Instead, it considers the ways in which future technologies are predicted; what can and cannot be predicted about the technological future with accuracy; general predictions about future technologies; and how to reframe the prediction of future technologies to deal with uncertainty.

3.1 Why predict future technologies

There are many reasons why future technologies and their impacts are predicted.

Predictions can be used for marketing or created as a product to sell through books and newspapers. Consultants can make a living from making predictions [965] and consulting firms can use the publication of technological forecasts as a tool for 'thought leadership' (opinion formation) to influence public policy and to build brand awareness of their firms[24]. Characteristically, such forecasts are often spectacular (to draw the reader in), unfalsifiable which means that the authors cannot be shown later to have been wrong (although this may not be the intent), and typically inaccurate (see Section 3.4). Their motivation is to entice, amuse and titillate. There is no feedback mechanism to check the accuracy of the predictions. Whilst popular, there is little evidence these forecasts add value to government planning.

Technologists, technological entrepreneurs and business operators have an interest in optimistically forecasting their own technologies to influence the market and forecasting other technologies that may improve their own business. Much of the overoptimism of future predictions can be explained by self-interest [142]. Proponents of new technologies are motivated to overemphasise desirable prospects and downplay problems yet to be solved.

Some of the main challenges of predicting new technologies are that:

- At any one time it is extremely difficult to be aware of all currently available technologies and all recent research into new forms of technology.

[24] See, for example, the following reports published by major management consulting companies: *The shift index – uncovering the logic of deep change* [456]; *Why change now? Preparing for the workplace of tomorrow [263]; Technology, media and telecommunications predictions 2014* [266]; the website *Technology Forecast; University of the future – a thousand year old industry on the cusp of profound change* [335]; *Ten IT enabled business trends for the decade ahead* [667]; *Internet matters – the Net's sweeping impact on growth, jobs and prosperity* [668]; *Manufacturing the future – the next era of global growth and innovation [645]; and Disruptive technologies: advances that will transform life, business and the global economy [644].*

- The adoption of technology relies upon having the right skills available (Sections 2.9.3, 7.4).
- Technology and infrastructure are interdependent in complex ways (Section 2.2).
- Since price is a crucial factor in any technology decision, it is necessary to be able to predict all of the costs associated with new technologies (Section 6.4).

Predictions are highly dependent upon assumptions about the past, present and future. When people think about the future, they are limited by knowledge of the past and present. Experts fare no better than other people at predicting the future forms of a technology and their impacts. As Rosenberg wrote,

> Thinking about the eventual impact of a drastically new technology is severely handicapped by the tendency to think about them in terms of old technology. It is difficult even to visualise the complete displacement of an old, long-dominant technology, let alone apprehend a new technology as an entire system [908].

There are other reasons for the difficulty in prediction, apart from imagining the future in terms of the present. Rosenberg noted elsewhere

> Inventions typically enter the world in very primitive form compared with the shape that they eventually acquire', and 'often appear distinctly unpromising at the outset. Their dominating characteristics are often high cost and poor performance standards, including an infuriating degree of unreliability [597].

3.2 The nature of prediction

The challenges in predicting technological change can be better understood by understanding the challenges of prediction in general. From the ethylene-induced visions of the Delphic oracle [140] through to the bizarre methods of divination used in centuries past[25] to the dubious but profitable business of selling predictions today [965], people want to know the future, and there is no shortage of those willing to indulge that desire [94]. The prediction of future technology is no exception. Views of the future have always been polarised, from concerns expressed in Plato's dialogue *Phaedrus* that the diffusion of the new technology of writing will degrade people's memories [835], to a long line of utopian and dystopian forecasts expressed in all forms of literature and media [59,808,839].

Even those who are not trying to create technology look to predictions to guide their business decisions or government policy, or simply feed their curiosity. Whatever the prediction, the progress of technological change is far from uniform, and all new technological developments have potential for both benefit and harm.

New technological developments, products and processes, and the impacts of such predictions, can be understood in a variety of ways:

- **Specific numerical performance indices** – for example, Moore's law, popularly known as a prediction of the number of transistors that can be placed onto one silicon chip. It has been more accurately described as a method to motivate toward a specific goal which therefore becomes self-fulfilling.
- **New fundamental technologies** – for example, new types of nuclear reactors such as thorium cycle reactors [523,752,1146]. The potential for development or commercialisation or scaling of these fundamental technologies is foreseeable

[25] See the catalogue in the third book of Francois Rabelais' *The heroic deeds and sayings of the worthy Pantagruel* including pyromancy, aeromancy, hydromancy, lecanomancy, catopromancy, aleuromancy and alectryomancy, the last involving a rooster pecking out a message from seeds placed on letters!

(generally by experts) once basic prototypes or the principle of operation are clear. What is much more difficult is to accurately forecast their use and the timing of their adoption (Section 3.4).

- **New-found uses for current technologies, 'adaptations'** – results of the process by which technological features acquire functions for which they were not originally intended or adapted. The CD-ROM, for example, was developed for music but was then used for storing data [280].
- **Changes in the way current products work** – for example, that smart phones will have 3D screens [807].
- **Enabling effects on other technologies** – for example, pervasive computing will enable new ways of managing road traffic.
- **The degree of uptake of technology** – for example, the fraction of electricity generated by solar photovoltaics.
- **Predictions of solving persistent or difficult social problems** - there is consensus that the world needs to find ways of generating energy without creating carbon pollution; there are many possible technological options. It is reasonable to predict that one or more of these options will succeed at scale. But it is not possible to predict which one will be successful, or when this might happen.
- **Economic effects** - for example, contribution to gross domestic product, reduction in the price of goods and services due to technological change, and investment decisions.
- **Environmental effects** – for example, climate change due to carbon pollution and the development of sensors to measure environmental changes.
- **Metrics** associated with technological change – for example, number of patents issued.
- **General themes associated with technological change** – for example, increase in 'personalisation'; infrastructure lags contribute to technological inertia; change happens faster/slower today; technology is becoming autonomous and will take over human control; the convergence of existing disciplines (e.g. physics, chemistry and life sciences); everything has already been invented.
- **Quasi-religious events** – for example, the singularity is coming (the 'hypothesis is that accelerating progress in technologies will cause a runaway effect wherein artificial intelligence will exceed human intellectual capacity and control, thus radically changing or even ending civilization') [1098,1127,1160].

A key attribute of a prediction is its accuracy. How accurate are future technology forecasts? The retrospective analysis of technological predictions is a rarity, but such studies have found that often those who are asked about their inaccurate past predictions cannot remember making them in the first place [1034]. Tetlock, in his study of the reliability of expert predictions had to confront the 'methodological nuisance' of experts who misremembered their predictions as being more accurate than in fact they were at the time of making them [1034]. He said, 'It is hard to ask someone why they got it wrong when they think they got it right'. This inability to acknowledge when a prediction was actually wrong is widespread [946,1031], and is closely related to the overconfidence people typically have in their beliefs [425] (Sections 5.2.4, 6.4.2).

Although there is ample compelling evidence regarding the fallibility of prediction of technological change - especially the prediction of the specific impacts of particular technologies - prediction has retained a fascination for many concerned with technology and its impact on society. Whilst undeniable that future technologies will affect the far future, the near future will be affected by a mixture of new, current and old technologies. Because of the natural timescale for dramatic technological change (often many decades, particularly when there are large infrastructural elements) the technologies that affect people most now (e.g. textiles, concrete, agriculture, telephone, electrification and automobiles) are centuries or millennia old [321].

One can anticipate or predict specific technological developments with reasonable accuracy over a sufficiently short time. This gives hope that one can predict events accurately further into the future, given enough information about the present, but the hard truth is that we can know very little about what the eventual impact of a new technology may be, even after it has proven to be workable. Those potential future uses can be attained only after years or decades of development activity (the D of R&D) [911].

3.3 How is future technology predicted?

There have been many quantitative and qualitative techniques developed to predict future technology development – inventors imagining the impact of their invention; expert opinions; science fiction; scenarios; horizon scanning and monitoring; scientometrics, bibliometrics and patents; and hypotheses of technological progress [531].

No single forecasting technique is best. Different techniques are used in different industries. The pharmaceutical industry, being science-driven, tends to rely on publication citation analysis because new scientific research is key to competitiveness. A market-driven industry such as telecommunications might use roadmaps and scenario analysis [361]. This section summarises the most widely used techniques.

3.3.1 Inventor imagination and inspiration

Over time, 'inventors' of what turn out to be important and impactful technologies have often tried to foresee the major and economically important uses of their technology, with surprisingly poor success – as Socrates quoted the ancient Egyptian king Thamus,

> The discoverer of an art is not the best to judge of the good or harm which will accrue to those who practise it. – Plato, *Phaedrus*, 274.

There are many well known inventions whose uses and impacts were not foreseen by their inventors [910]. These include:

- **Lasers** Perhaps the most significant economic use of lasers is in conjunction with fibre optic cables, where they form the backbone of modern international telecommunications systems. At the time of invention, in the word of Charles Townes (the 'inventor'), 'Bell's patent department at first refused to patent our amplifier or oscillator for optical frequencies because, it was explained, optical waves had never been of any importance to communications and hence the invention had little bearing on Bell System interests' [1052].
- **The phonograph** Edison (who is typically given credit as the inventor) detailed a list of possible uses [280,322]. His predicted uses, in order, were: 'letter writing, and other forms of dictation books, education, reader, music, family record; and such electrotype applications as books, musical-boxes, toys, clocks, advertising and signal apparatus'. And his prediction with regard to its use in music missed the main value: 'A friend may in a morning-call sing a song which shall delight an evening company, etc.' A decade later he interpreted his earlier predictions as being accurate, when perhaps they were not, claiming that he 'predicted only that which has now fulfilled' [323]. The positive aspect of his predictions was that there were many, not one; he was wise enough to predict 10 separate uses all of which can be seen to have come to pass in *some* way, but he did not and *could not* have accurately predicted the dominant commercial use for the sale of pre-recorded music.
- **The steam engine** was originally developed as a pump to aid mining. Its various later uses were not envisaged at the time [904].
- **The telephone** Western Union failed to take up the telephone when offered. Note that Bell's invention was of a device for 'multiple telegraphy' – he was not trying to invent the telephone [675,842].

- **The transistor,** perhaps one of the most profound and widely applicable inventions of the 20th century, was in its early days thought to be primarily valuable in hearing aids [910].

The point of this long list of failures of imagination is not to deride and ridicule those past inventors who could not envisage a future[26], but to check the hubris of those who think they could do any better (Section 6.4.2). It would be an astonishing act of imagination in the 1940s to predict the computers of 2015. The gas-turbine when first developed had 15 times worse power-to-weight ratio than a piston engine. One year later it was twice as good as a piston engine. Inventions typically come into the world in a very primitive state and improve through iteration over varying and generally unpredictable timescales (Sections 2.9.1, 7.5).

More generally, predictions can inspire efforts to realise the envisaged future. This can be viewed as propaganda [968] or an empowering and enabling vision that changes the way people imagine the future and future technologies (Section 5.1.4):

> There is a way for us to change the future for the better. We can change the future by changing the story we tell ourselves about the future we are going to live in [38,534].

There are many technologists whose valuable developments have been inspired by such stories. David Skellern, co-founder of Radiata, the Australian company that made the first functioning CMOS WiFi 802.11a chipset, has said that his 'inspiration for the project to a considerable extent arose from the 1987 HP visionary short video called *1995* that envisaged people watching streaming video on wireless tablets. Skellern was inspired to ask, 'How do we make wireless data fast? How do we make it small? And, how do we do both so that the solution is affordable and would actually be widely used'. He then set about developing a system that could do just that [972].

3.3.2 Ask the experts?

Science is the belief in the ignorance of experts.

Richard Feynmann [356]

A popular method to forecast future technologies and their impact is simply to ask an expert[27]. The issue is the accuracy of the answer (Section 3.4). Anyone can declare themselves an expert

---

[26] Lest scientists feel superior in contemplating the apparent stupidity of technologists in not being able to foresee the impact of their own inventions, all of the above failures of foresight are dwarfed by the astonishingly wrong pronouncement of Thomas Bell FRS, the president of the Linnean Society, which in 1858 had published Darwin and Wallace's revolutionary account of the origin of species [238]. In his presidential address of 24th May 1859 to the society on the anniversary of Linnaeus's birth, Bell said in reviewing the scientific progress of 1858:

> It has not, indeed, been marked by any of those striking discoveries which at once revolutionize, so to speak, the department of science on which they bear; it is only at remote intervals that we can reasonably expect any sudden and brilliant innovation which shall produce a marked and permanent impress on the character of any branch of knowledge, or confer a lasting and importance service on mankind. A Bacon or a Newton, an Oersted or a Wheatstone, a Davy or a Daguerre, is an occasional phenomenon, whose existence and career seem to be especially appointed by Providence, for the purpose of effecting some great important change in the condition or pursuits of man [98].

Nowadays Darwin is held in higher esteem for the impact of his discovery than all of those named, with the possible exception of Newton.

[27] It is fashionable for historians, biographers, and journalists to treat defunct dignitaries and departed experts in other fields as though they had unusual prophetic insight in the area of technology. Too much is read into the correspondence between a current item of technology and

and then make a prediction, but often these pronouncements are simply opinions. Even widely acknowledged experts can be surprisingly bad at accurate predictions. Kerr presented the results of predictions of the success of start-up companies (most start-ups are heavily dependent on new technologies). Even the partners at this successful firm (who invested more than $1billion over the last decade) had no predictive ability at all regarding which firms would be great successes and which would fail [561].

It has also proven popular to combine the opinions of multiple experts using the Delphi method [236]. This method combines expert opinions concerning the likelihood of realising a proposed technology as well as its expected development time. A sequence of individual interviews with experts is followed by feeding back analysis of the collated interview results to the individuals. The feedback, which includes reasoning and justification, allows the other experts to revise their forecast in the light of the new information. After several rounds, a single acceptable forecast is usually agreed on. Although the Delphi method can successfully bring a group of experts to a consensus, it has been criticised for the group pressure it places on those experts to conform to the group [592].

It is instructive to look at expert opinions published some time ago, so one can gauge how well they did (Section 3.4). It is possible to find examples that: 1) seem remarkably prescient; 2) are spectacularly wrong; or 3) make no sense now. Of course this can only be done in hindsight. The following list, spanning a century, illustrates the ongoing fascination for technological prediction, and the rarity of humility of the forecasters.

- Edward Bellamy (1888), *Looking backward, from 2000 to 1887* [99]
- Robert Prehoda (1967), *Designing the future – the role of technological forecasting* (still proposing the use of nuclear explosives for mining; human hibernation; and ends by suggesting that widespread technological forecasting could ‘serve as a foundation for successive steps leading to permanent peace’) [851]
- Stephen Rosen (1976), *Future facts: a forecast of the world as we will know it before the end of the century* [903]
- Gerard O’Neill (1981), *2081: a hopeful view of the human future* [779]
- Norman Macrae (1984), *The 2025 report: a concise history of the future 1975-2025* [640]
- Brian Stableford and David Langford (1985), *The third millennium: a history of the world AD2000-3000* (fusion power, widespread genetic engineering, colonisation of planets, but imagined the Soviet union would not fall) [992]
- Daniel Bell (1987), *The world and the United States in 2013*, Bell, a renowned sociologist, made a technological prediction and was clever enough to keep it general: ‘By 2013 the third technological revolution – the joining of computers and telecommunications (image television, voice telephone, data information computers, text facsimile) into a single yet differentiated system, that of the ‘wired nation’ and even the ‘world society’ – will have matured’ [96])
- Adrian Berry (1996), *The next 500 years: life in the coming millennium* [106]
- James Canton (2006), *The extreme future: the top trends that will reshape the world in the next 20 years* [162] (widely off the mark after only 10 years)
- Michio Kaku (2011), *Physics of the future: how science will shape human destiny and our daily lives by the year 2100* [550]
- Peter Scott-Morgan (2012), *The reality of our global future: how five unstoppable high-tech trends will dominate our lives and transform our world* [954]

What one will almost never find is an admission of how unreliable these predictions are. As with most other areas of human endeavour, not only technological prediction, expert opinions should be treated sceptically.

---

a vagrant anticipation by a famous man – and too little attention is paid to the absurd and erroneous forecasts he may have also bothered to make [968].

3.3.3 Science fiction as prediction

Science fiction can take many forms (e.g. books, movies and comics) to explore future technologies and their implications. The authors of such fictional works can sometimes present remarkably accurate predictions of technological change. In the early 19th century, Mary Shelley produced what is considered the first work of science fiction, *Frankenstein*. The story was written in the time of massive technological development during the Industrial Revolution and explored how society could be transformed by scientific endeavour and what came to be called technology. Today, science fiction enables creative thinking about science and technology by looking at the potential social and ethical implications of new technologies. Science fiction prototyping can contribute to the development of new technologies [535]. Such literary speculations can serve a serious purpose in getting contemporary technologists to think differently. For example, Intel has sponsored science-fiction authors to help them imagine new technologies which they may well be in a position to invent [38,292,535].

As with all prediction activities one needs to take care regarding hindsight bias – there are plenty of predictions that are false, and furthermore there are many that only seem true by a generous interpretation of what is a very broad brush prediction. This is not to say these predictions are of no use as they can inspire future technology creators and users (Section 3.3.1). There is no evidence that science fiction authors have any privileged method that is more accurate to predict technological change. The value is not in the specifics of the products or the processes that they describe or anticipate, but in the role they play in inspiring others to work towards creating an imagined future. You may not end up with a Jetsons Car or a hoverboard, but you may end up with all sorts of useful 'spin-offs' in the attempt.

3.3.4 Scenarios of the future

A scenario is an imagined future state of the world. Scenario planning does not produce a forecast but assumes one which is instrumental in imagining the future environment. Consultants in business and politics often use scenario exercises to encourage decision-makers to imagine a broad array of possibilities [949]. Scenarios are better suited to forecasting the impact of situations than forecasting technologies. The scenario approach is useful as a complement to other forecasting approaches in that it can elucidate some of the factors which may affect the topic of study [927].

Scenarios can provide value in contingency planning by helping to ensure future plans are robust against multiple possible outcomes, and like science fiction, they can also inspire an outcome.

However scenarios do not improve the accuracy of predictions [1034]. Whilst often seemingly radical and imaginative at the time of their creation, scenarios of the future tell you more about the past and the present in which they are anticipated. Nevertheless, scenario-based thinking remains popular, perhaps because it suits the tendency of human beings to draw on readily available examples [717], (Section 5.2.4).

Scenarios can fail because of failure of imagination. Amara's Law (due to Roy Amara of the Institute for the Future) states that we overestimate short-term changes and underestimate the impact of technology in the long term [957]. It turns out to be harder for people to be imaginative about the future than about the past:

> When people are asked to use their imagination to complete an unfinished story and that story is supposedly laid in the past, the tale tends to be given a rich and interesting conclusion. Yet, when people are asked to complete the same story as something that will happen in the future, the added endings will be sketchy and unreal … Our power of creating a mental future lies in our ability to imagine the remote consequences of present acts, to create new combinations of act and consequence, to connect present feelings and motives to those consequences, and to suppress or to de-emphasize the present stimuli that would otherwise deflect our attention from those future events [635].

Recent neuroscience offers some support for Lynch's claim concerning imagining of future scenarios; Spuznar et al. showed that human brains place a scenario in a well known spatial contexts [1022]. Furthermore, the types of futures envisaged are affected by people's goals and by the timeframe chosen. They become more abstract and general the further they are set in the future [187]. How people envisage the future is still not well understood [146,148,418,937]. While scenarios written in the present might sound bold and imaginative, past ones, such as those in *Developing long-term strategies for science and technology in Australia* [53], seem rather flat and unreal. The world is richer and more interesting than human imagination can conceive; see Box 8.

In his essay 'Hazards of prophecy: the failure of imagination', Arthur C Clarke suggests:

> One can only prepare for the unpredictable by trying to keep an open and unprejudiced mind - a feat which is extremely difficult to achieve, even with the best will in the world. Indeed, a completely open mind would be an empty one, and freedom from all prejudices and preconceptions is an unattainable ideal [188].

The unexpected	The expected
X-rays	automobiles
nuclear energy	flying machines
radio, TV	steam engines
electronics	submarines
photography	spaceships
sound recording	telephones
quantum mechanics	robots
relativity	death rays
transistors	transmutation
masers; lasers	artificial life
superconductors	telepathy
superfluids	invisibility
atomic clocks	levitation
detecting invisible planets	teleportation
determining composition of celestial bodies	communication with dead
dating the past (carbon 14, etc.)	observing the past, the future

Box 8: The element of surprise: unexpected and expected technologies (drawn from [188]). The right column is a list of technologies that 'late nineteenth century scientist' would have reasonably expected to be developed; the left column are technologies that the vast majority of such scientists would have been very surprised about.

Clarke goes on to make the following point:

> All the items on the left have already been achieved or discovered, and all have an element of the unexpected or the down-right astonishing about them. To the best of my knowledge, not one was foreseen very much in advance of the moment of revelation. On the right, however, are concepts that have been around for hundreds or thousands of years. Some have been achieved; others will be achieved; others may be impossible. But which? [188].

The point is that the unimaginable is not able to be imagined. People need to be prepared to be surprised. Scenarios can be useful to enable robust planning and they can be excellent for spurring invention [535].

3.3.5 Horizon scanning and monitoring

Horizon scanning and monitoring are used to examine potential threats and opportunities and likely future developments. They are a systematic attempt to look broadly for new sources of information. Monitoring can inform an organisation of changes on the horizon that could affect the uptake or acceptance of a technology. This method can find early indications of possible future developments to enable as much lead-time as possible. Given the breadth of potential impacts, such an exercise seems unnecessary if one attempts to do it once for all possible users. The Australasian Joint Agencies Scanning Network is a group of government agencies from Australia and New Zealand. The group jointly identifies anomalies, emerging issues, game-changing events and developments from a wide range of literature and media. The systematic collection of material by such groups can be valuable, however retrospective analysis of scanning exercises are required to measure accuracy and the impact such exercises make in government decision making.

Horizon scanning does makes sense as part of an organisation's ongoing processes for looking for new opportunities – see, for example, IBM's 'Horizon Watch' [174]. Since radical innovation often comes from 'outside', it is valuable to make a systematic effort to look outside one's existing expertise base [183,533].

3.3.6 Counting citations, patents or other numbers

An appealing idea is that if technological development could be quantified and measured, it might also be possible to predict it more accurately and consistently. One instantiation of this idea is to analyse publications or patents. Patent statistics in particular have had a long history as aggregate measures of 'inventive activity' but as 'Both the inputs and the outputs in the production of invention are appallingly difficult to measure', using patents statistics in this way is beset with difficulty [913]. Not all patents are equal: not every invention is patented, and there is no logical reason for any strong relationship between impact and the degree of patent activity[28].

The apparent objectivity of patent statistics has led to the idea that one can forecast future technologies using patents. But while patent numbers are precise and unquestionable, it is unclear what such aggregate numbers actually measure. The vast literature cited previously clearly indicates the difficulties of trying to reduce technological progress to a single statistic.

Analysis of patent data *can* be valuable, particularly when it is used within technology development organisations to identify areas in the patent landscape where technological advance may be possible and profitable. For example, keyword-based patent maps can statistically categorise what is patented so that it is easier to identify where the patent gaps are [359,606,642]. This allows identification of rapidly evolving technological trends for R&D planning using subject–action–object based semantic patent networks. These statistically categorise what is patented so it is easier to identify where the patent gaps are. Such an approach can be extremely valuable within a particular domain where one already has sufficient expertise to evaluate the opportunities. It is impossible to do this globally across all technologies and therefore this report has not made use of patent analyses.

Although the level of patent activity that occurs within a technological area can indicate there will be some impact, it is impossible to be more precise. All of the factors that affect the complexity of technological forecasting remain, even with the patent statistics. This has not stopped the proposal of complex statistical methods [234], although there seems to be no evidence that these methods lead to accurate forecasts of technological input.

3.3.7 Hypotheses of technological progress and extrapolations

If it was possible to reduce aspects of technological change to a number, or a small set of numbers, one could in principle use any of a wide range of mathematical prediction methods as

---

[28] See [30,83,284,423,447,448,459,461,564,593,623,753].

a means of forecasting technological change through the observation of trends and straightforward extrapolation. This might lead to real insight, but it could also be misleading because of the false sense of accuracy engendered.

Hypotheses of technological progress are used in predicting the trajectory of technological development and cost. One of the first examples of these was made by Theodore Wright, who in 1936 predicted that the cost of technology would decrease as a power law of cumulative production [1152].

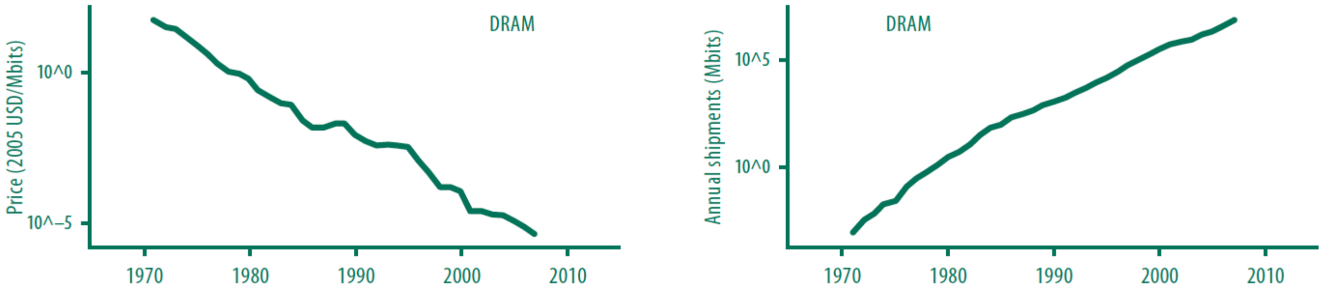


Figure 6: The price of DRAM (Dynamic Random Access Memory – the memory 'chips' used in computers) as a function of time on the left, and the total production as a function of time on the right, based on industry-wide data. Vertical axes are logarithmic. Reproduced from [736].

The most widely known example of a hypothesis of technological progress is 'Moore's law'. In 1965 Gordon Moore observed that the number of transistors that could be placed on an integrated circuit had doubled every year. He predicted this trend would continue [715]. Moore looked at the circuits being produced, plotted their density and found a straight line. He made his observation when the integrated circuit was only six years old. The prediction has held true except that the interval for doubling extended from 12 months to 18 months.

Another hypothesis of technological progress is illustrated in Figure 6 which shows the variation in unit price and volume of shipment of a type of computer memory chip. The measured data are remarkably well fit by a straight line (note the logarithmic vertical scale). One can trivially form a prediction from such data by linearly extrapolating the line. Such a method of prediction does not explain *how* the improvements will be obtained. The continued empirical validity of this law, is a consequence of a very large number of diverse factors, both technological and economic. It can be argued that the empirical regularity is caused in part by organisations learning how to do things better [31].

These empirical regularities can be used in an obvious way to make forecasts. For example forecasts on photovoltaic module price and system price can be made by extrapolating empirical data on appropriate scales [160]. Figure 7 shows a plausible prediction of future prices simply by extrapolating the overlaid straight line. When applied to the system level, because of the larger number of determining factors, the empirical record is less regular, and thus less predictable (Figure 8).

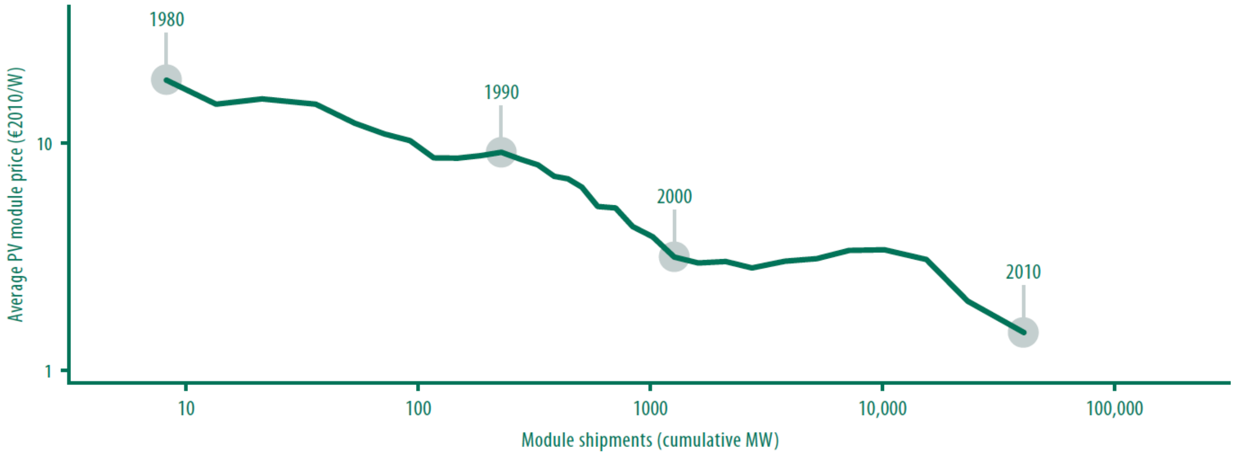


Figure 7: Average PV module price as a function of cumulative shipments. This shows that as time passes, the cumulative module shipments rises substantially (note the logarithmic scale) and at the same time the average price per module declines (also note the logarithmic scale). Sourced from [160].

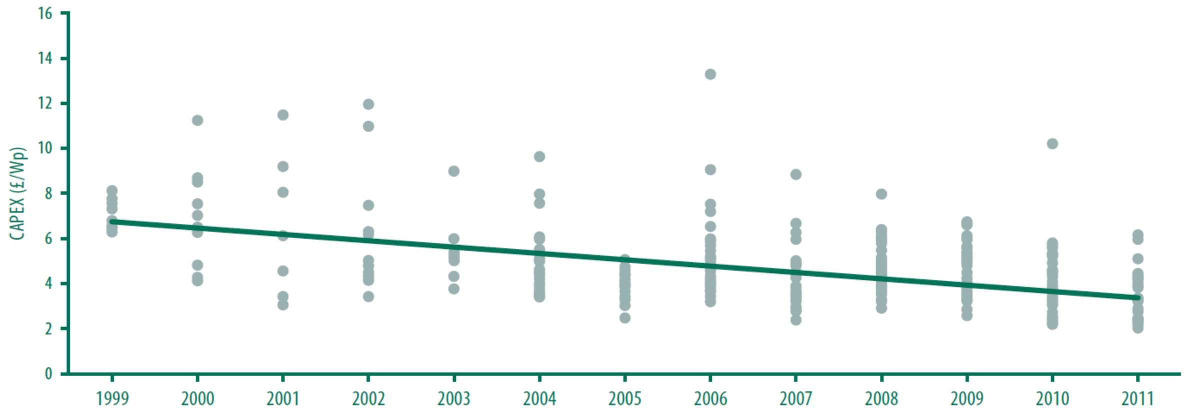


Figure 8: Distribution of PV system prices (per rated capacity) as a function of year. Sourced from [160].

Moore's law has been used as a roadmap for the semiconductor industry [142,173,638,1020]. Such predictions of technological change can also work as incentives. Moore's law has proven to be remarkably accurate. It is widely viewed now as a self-fulfilling prophecy since it inspired and motivated industry and research action to achieve a doubling of the number of transistors per chip, [681,1089]. The prospective and simple forecast became an industry target to be achieved. While it pushes the industry to greater and greater levels of performance, this target is not universally believed to be the best way forward. Robert Colwell, Director of microsystems technology office at the US Defence Advanced Research Projects Agency, argued the lapsing of Moore's law could actually offer more opportunities to the industry. Instead of focusing on reducing chip size and cranking up processor speeds, engineers could focus on changing the fundamental microprocessor architecture to ensure that chips are faster and cheaper to produce [961].

Predictions of the return of Hayley's [Halley's] Comet do not influence its orbit but the rumoured insolvency of a bank will affect the actual outcome. 'If men define situations as real, they are real in their consequences', W.I. Thomas. The self-fulfilling prophecy is, in the beginning, a false definition of the situation evoking a new behaviour which makes the originally false conception come true. For the prophet will cite the actual course of events as proof that he was right from the very beginning [336].

Box 9: Self-fulfilling prophecies

Since the empirical regularity of the increased number of transistors per chip has held true for so long, it has been given the name of a 'law', but of course the doubling cannot continue forever [214]. Some analysts have been predicting the failure of this law for many years, often placing the predicted failure 10 years from the time of prediction – predictions made in 1994 anticipate failure in 2004, for example, and predictions in 2004 anticipate failure in 2014. Ultimately economics and not physics will end Moore's Law when it no longer makes business sense [305]. Colwell has predicted that this will happen in about 2020, with a geometry scale of 7nm – the size of the smallest feature on an integrated circuit [961].

Even supposing Moore's law and related observations continue to be accurate for years, this does not imply accurate prediction of the end-use of technology. Having twice the number of transistors on a chip does not necessarily mean that the chip works twice as fast – because of the difficulties of programming more complex architectures, it could be less than twice. Advances in algorithms (the mathematical procedures which underpin the computer programs) are likely to produce improvements in effective speed that dominate any improvements in raw speed caused by greater component density[29] [854]. Advances that can lead to order of magnitude improvements are almost entirely unpredictable. Apart from the vague prediction that there will continue to be advances, there is no basis for predicting how fast they will be or what their impact will be. It is possible that algorithmic breakthroughs could occur that would have a substantial impact on what can be computed efficiently. When that might occur is unknown.

Over the same period that Moore's law has held, computer disk memory capacity and fibre optic cable bandwidth have also increased exponentially (i.e. by a multiplicative factor per unit time) [173]. There is a tendency to expect a similar growth curve with other technologies and products, but there is no reason why this should be so universally. The exponential model of technological change can only be sustained by selecting just the right examples and ignoring all other examples. Technology does not always continuously improve. Technological change is not exponential in general – the first 40 years of building skyscrapers saw building heights increase fourfold, but over the next 40 years building heights did not increase much. There is a similar trend in the building of bridges, dams and ships. In many cases there are fundamental physical effects that preclude such steady exponential improvement. There are also many reasons for the end to a technology's fast growth phase whose basis may be economic; regulatory disincentives; social resistance; saturation; external events and other technical obstacles [957].

Hypotheses of technological progress can be useful in the short term, but are increasingly risky if one looks further to the future. They can be useful as self-fulfilling prophecies for industries. They manage to predict general forms of progress without being able to explain how the progress is to be attained, but they do not universally hold.

---

[29] There are orders-of-magnitude difference between what Moore's law provides and what algorithmic advances provide:

> In the field of numerical algorithms, however, the improvement can be quantified. Here is just one example, provided by Professor Martin Grötschel of Konrad-Zuse-Zentrum für Informationstechnik Berlin. Grötschel, an expert in optimization, observes that a benchmark production planning model solved using linear programming would have taken 82 years to solve in 1988, using the computers and the linear programming algorithms of the day. Fifteen years later – in 2003 – this same model could be solved in roughly 1 minute, an improvement by a factor of roughly 43 million. Of this, a factor of roughly 1,000 was due to increased processor speed, whereas a factor of roughly 43,000 was due to improvements in algorithms! Grötschel also cites an algorithmic improvement of roughly 30,000 for mixed integer programming between 1991 and 2008 [854].

3.4 The accuracy of technology predictions

In order to evaluate the accuracy of technological forecasts, it is necessary to return to the forecasts afterwards and examine their performance. This is rarely done – most forecasts from the past are forgotten as soon as they are made[30].

Looking at the accuracy of past technological predictions by criticising technological forecasts is almost as old as the forecasts themselves. Like the predictions themselves, which are usually done for a purpose [968], the analysis of past predictions can similarly be distorted to try and support a particular point of view. For example, in the widely discussed paper forecasting a decline in US economic growth [438] Gordon cites some technological predictions from the *Ladies Home Journal* in 1900 [1116], and cannot resist what might be called the Nostradamus effect: interpreting vaguely stated and carefully selected future predictions in a positive light to conclude that 'there were enough accurate predictions in this page-long three-column article to suggest that much of the future can be known'. Gordon makes this argument for a reason: he is trying to demonstrate that the rate of technological advance is slowing (as that supports the thesis he is trying to defend) [438].

Journalists are also prone to the selective use of predictions. The BBC, for example, in interpreting the predictions made in the *Ladies Home Journal* in 1900, was very generous in its assessment of accuracy, and the author did not discuss Watkins' predictions of the extermination of mosquitoes, flies and roaches (which, as this report went to print was yet to occur!) [407,1116]. A recent example is David Wogan's *Scientific American* blog in January 2014 claiming that many of the science fiction author Isaac Asimov's 1964 predictions have come true – robot-brain vehicles, battery-powered appliances, and increasing life expectancy, for example [1141]. A closer look at Asimov's article reveals just as many inaccurate predictions – including underground housing, hovering transport, moon colonies, household appliances powered by radioactive batteries, and pneumatic tubes used to transport goods around the city [40].

To be fair, those critical of predictions and forecasting can also cherry-pick failed attempts [941]. One way to avoid cherry-picking is to be as comprehensive as possible. Perhaps the fairand comprehensive analysis of the accuracy of technological forecasts was done by George Wise [1139]. His analysis was based on a collection of 1556 diverse technological forecasts made between 1890 and 1940. The predictions concerned changes to technology, or the social, economic, or political impacts of such changes. His range of technological areas was very broad. He showed empirically that predictions of the change of technology itself are significantly more accurate than predictions of technology adoption, use and impact [1138,1139]. He concluded:

> Overall, less than half of the predictions have been fulfilled or are in the process of fulfilment. The accuracy of predictions appears at best weakly related to general technical expertise, and unrelated to specific expertise. One expert (or non-expert) appears to be as good a predictor as another. Predictions of continuing status quo are not significantly more or less accurate than predictions of change. Predictions of the effects of technology are significantly less accurate than predictions of technological changes [1138].

Wise found experts predicted only slightly better than non-experts – 'batting average' of 44% correct (expert) vs. 34% (non-expert) – although as Wise says, the distinction between expert and non-expert is somewhat hard to defend. Wise concluded, 'In retrospect, it appears that social and economic conditions evolve in response to the entire complex of technology, rather than to a single innovation'. Systematic expert aggregation methods such as Delphi have not been proven to be any more accurate than other judgement methods. In fact studies have

[30] See, for example, the technological utopianism of *Popular Mechanics* in the 1930s [101], and most of *Wired* magazine today.

indicated that experts produce no more accurate predictions than non-experts [21,636,812,934,1046,1148].

A more recent systematic study of the accuracy of technological prediction examined the technology forecast assessments of a study conducted in the early 1990s, the US Strategic Technologies for the Army of the Twenty-First Century (STAR21) [636]. The forecasts aimed to identify the advanced technologies most likely to be important to ground warfare in the 21st century. The 104 forecasts were judged by Army senior scientists and engineers. Results were divided almost evenly between those judged to be about right, those which overestimated progress, those which underestimated progress, and those which were wrong or missed entirely. The timing of many of the predictions was wrong by a significant amount. The review noted that the people who did the original studies offered the weak argument that even though the predictions were wrong in many senses, 'such a study helps them to justify their program plans and budget proposals by informing Army leadership of the future importance of these technologies' [636].

It is hubris to suppose that people today are better at predicting future technological change than people in the past. Some future technologies are unexpected or unpredictable. To calibrate what sort of prediction accuracy is achievable, it is useful to analyse the accuracy of past predictions. Phillip Tetlock did this with the predictions of expert political commenters, and showed that in most cases their predictions were worse than random (they would have been better off flipping a coin) [1034]. His most valuable finding was that those who were most certain of their one single way of viewing the world were substantially more likely to be wrong than the those who did not hubristically presume they had the one true theory of the world. This finding - that experts tend to be unjustifiably more optimistic about the correctness of their forecasts - has been replicated by others [1046]. Tetlock's most ironic finding was that those who did make (seriously) wrong forecasts could not even recall their own forecasts, often attributing to themselves the opposite (but correct) forecast to that which they made; the psychology of such history rewriting is pervasive and becoming well understood. As Kathryn Schulz notes, 'As a culture, we haven't even mastered the basic skill of saying "I was wrong"' [946]. Technologists have generally mastered this skill, with systematic methods of dealing with, and learning from failures of technology, but it is not universally practiced when forecasting [831,833].

It might be argued that by using more data, one could do better complex mathematical calculations to aid prediction. But there is no evidence that complex mathematical models predict technological futures in general any more accurately than simple models [941]. Many of the forecasts derived from complex mathematical modelling have been wrong. As can be seen in Section 3.3.7, mathematical curve fitting can lead to absurd and now well-falsified predictions. Figure 9 shows that airplane speeds now are nothing like what was predicted. However, when applied sufficiently narrowly to sufficiently short-prediction horizons, straightforward extrapolation can be remarkably accurate. But such simple extrapolations, even if done with more complex mathematical methods, do not seem to offer much value.

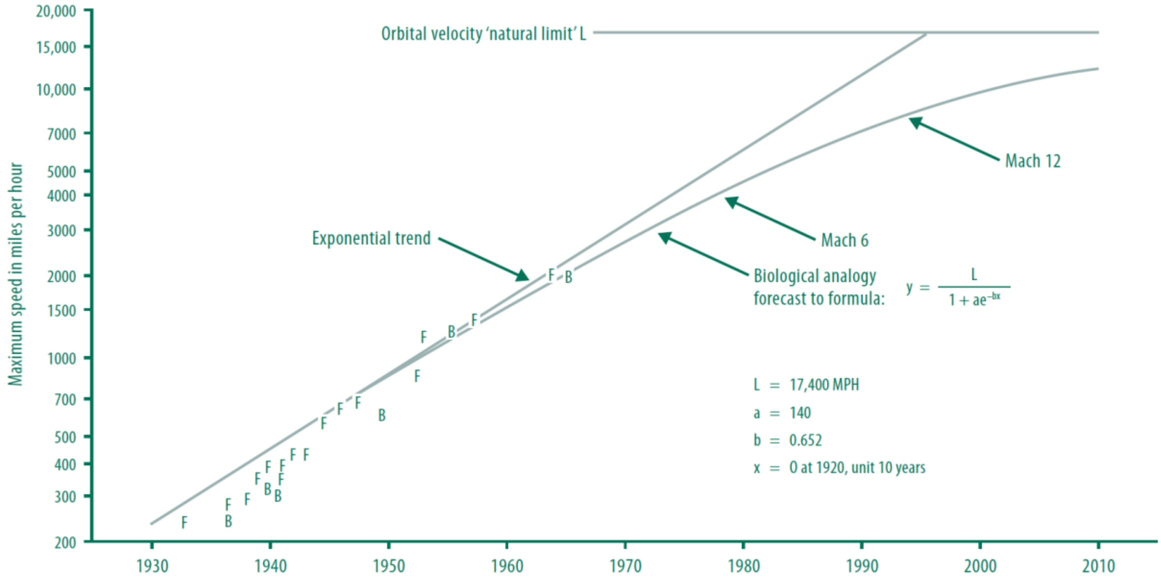


Figure 9: Speed trends of US aircraft predicted by simple curve-fitting. Current maximum aircraft speeds fall far below either of the predicted curves, illustrating the danger of simple-minded extrapolation as a means of predicting future technologies. Sourced from [524].

The most substantial attempt of technological forecasting was the 1937 report *Technological Trends and National Policy [745]*. The forecast identified thirteen inventions that were expected to have a profound impact on business and society within 10-25 years of the date in which the forecasts were made.

Campbell et al. evaluated the 1937 forecast and their assessment (combined with our own assessment) is summarised below [159]:

TV - correct in many of its predictions: many aspects are regulated; continuing concern over the material which children might view; effect on politics was spot-on (they predicted it would become shallower and more about appearance than substance); impact on education and proliferation of sitcoms, talk shows and channels was not predicted. 3D – was predicted to be pervasive within 10 years; even now it is not (see discussion of 3D TV in Section 3.6.2).

Fax - widespread adoption much later than predicted; daily transmission of newspapers did not occur; main impediment was quality and speed of transmission.

Mechanical cotton picker - accurately predicted impact on farming, but slower than predicted.

Air conditioning **-** accurate predictions regarding timing, usage, social implications.

Plastics - predicted replacement of wood and metal; did not predict the proliferation and use plastics as materials of choice, rather than of replacement.

Synthetic rubber - growth in demand was fuelled during WWII.

Artificial cotton - predicted growth in synthetic fabric, impact on wood and cotton industry was overstated.

Photo electric cell - true but took longer than predicted, also found more application in everyday life than predicted, but did not have the revolutionary impact predicted.

Steep flight planes – technical limitations and safety requirements have limited this technology.

Prefabricated houses - small industry, did not predict that many components are now prefabricated.

Trailers - incorrect prediction for permanent housing, uptake has been in holiday use.

Tray agriculture - no impact.

Gasoline produced from coal - did not anticipate extent of new petroleum reserves found and deep drilling.

Schnaars et al. also examined the accuracy of the same 1937 forecasting report concluding [942]

- 46% did have a strong impact on business and society in subsequent decades, 31% moderate, 8% weak
- 62% innovations took longer than expected to penetrate markets, 38% within the 10-25 yr time
- 38% of the uses made were rated correctly, 38% had a mixed record, 23% were wrong
- 27% of social implications were correctly predicted, the rest were all or mostly wrong
- Lessons learnt included – avoiding overoptimism on timing, it is difficult to predict applications and uses, minimising the attempt to predict social implications, avoiding emotional language 'new era', and not relying on mathematical models with hidden assumptions.

A series of 'retrospective technology assessments' were performed in the 1970s [192,843,1024]. Two substantial evaluations were done concerning the technologies of submarine telegraphy [192] and the telephone [843]. These two studies are invaluable because they attempted a comprehensive assessment of past predictions rather than cherry-picking isolated predictions. The results are humbling[31]; sometimes predictions were accurate; in other cases they were way off the mark. Two general conclusions from the whole program are 'technology assessment should take a broader, problem-oriented perspective rather than focussing on specific technologies' [1024] and 'a technical–economic market analysis is the place to begin a successful technology assessment' [843] (page 12). The point here is that one can hardly make an assessment of technology impact without an understanding of the market. This conclusion was based on the finding that 'the best forecasts made about the telephone arose from just such analyses by people who both understood the technology and sought to assess how to implement it in a way that would pay.'

The four-volume 1980 report [200] of the Committee of Inquiry into Technological Change in Australia concluded that the prospects of accurately forecasting new technologies were poor:

> [The committee] did not believe that outcomes could be predicted with any accuracy or that particular technologies could be declared in advance to be 'good' or 'bad'. Democratic mechanisms and institutions in Australia were considered able to respond in ways generally acceptable to the community, section 3.2.2 of [52].

The accuracy of technological predictions is low. Several authors have speculated on the reasons for this:

- Some claim forecasters are seduced by technological wonder.
- Change (especially social change) comes more slowly than expected.
- Forecasts are based on what is important to society at the current time. Dominant themes of the day may not be as important in the future.
- Benefit cannot always be calculated quantitatively [941].

Authors of technological forecasts who recognise the manifold failures of previous forecasts do not think that their own forecasts will be similarly inaccurate. For example, the optimistic forecasts from the US Army are not tempered by the long list of reasons for failure of previous forecasts including

> unpredictable interactions, unprecedented demands, major unforeseen discoveries, inadequate data, complexity of the problem, lack of imagination, overcompensation, failure to anticipate converging developments or changes in competitive systems, concentration on specific

[31] Technology assessment *should* have a past, if only to prevent an attitude of overconfidence on the part of today's assessors. By rethinking the issues that confronted their predecessors, they can do more than learn history. They can appreciate how difficult a job technology assessment really is, even in retrospect [1024] (page 261.).

> configurations, incorrect calculation' and the final catch-all 'intrinsic uncertainties and historical accidents' [524].

Assessing future technology in the short term can lead to valuable insights and reasonably accurate predictions if a logical, economic and historical analysis is used [159]. A contemporary assessment of the 1980 report *Technological change in Australia* concluded that 'a nervous look confirms it's all unknowable' [878], quoted in [200,975]. It is not entirely unknowable (see Section 3.5) and there is no reason to be nervous (see Section 7.5).

3.4.1 Uncertainty and future technology prediction

The prediction of future technology is complex. The difficulties of predicting future technology are primarily due to the uncertainty of technological change [910]. The following factors contribute to uncertainty and complexity in prediction.

Predicting future knowledge. Since much technological advance is contingent on the growth of scientific knowledge, one would need to be able to predict the knowledge first [297,880]. Furthermore, *possible* future scientific knowledge is greater than what will actually come to pass, which itself exceeds current knowledge. This means that there is far too much scientific knowledge for any individual or group to assimilate [15].

Technology cost. Cost is one of the prime factors affecting technology investment and adoption Chapter 6. Retrospective analyses of technology assessment stress this point: a detailed study of the telephone concluded that

> for a technology assessment … one needs first to bring to bear a technical economic analysis that explains the investment and marketing possibilities of each technical alternative. The best forecasts made about the telephone arose from just such an analysis – how to implement it in a way that would pay [843].

Predicting a technology while ignoring the economic factors will not allow for accurate forecasts. But forecasting the economic conditions relating to a technology requires the prediction of the economy, which is itself difficult.

Predicting the use of a technology. Empirical regularities such as Moore's Law can and do hold for long periods. However, they give almost no guidance as to the adoption and social impact of a technology. Furthermore, cessation of a regular change (such as Moore's law flattening out) does not imply cessation of change in the use of the technology (Section 3.3.7). Also, steady improvement in performance characteristics of a technology can lead to a sudden change in technological impact. For example, the steady decrease in the cost of solar photovoltaic panels means that this technology may eventually become the cheapest form of electricity generation. Parity with existing grid prices is expected in 36 of the states in the US by 2016. This tipping point might significantly affect how energy is produced [871].

The parts-assembly nature of technology. More radical inventions take a broader collection of inputs because 'what is common to originators is not 'genius' or special powers. Rather it is the possession of a very large quiver of functionalities' [35]. That is, it is typically not a single discrete and unique innovation, but the collection and integration of many innovations. The parts-assembly and interoperability characteristics of technology mean that accurate prediction of a single new technology may require the accurate prediction of the advance of a large number of component technologies. This also makes predicting the long-term impacts of new inventions difficult. Sometimes these combinations are unplanned (serendipitous) which makes their prediction effectively impossible [382] (page 24). Substantial inventions such as the laser required compatible component development over long time periods to find its uses which are now extraordinarily diverse – surveying and measurement, medicine, telecommunications, computer components (e.g. disk drives, printers), manufacturing, scientific research, energy production, food packaging and analysis, and military applications.

Underpinning technologies and reverse salients. Every new technology depends upon a wide range of other technologies and infrastructure, whether in operation or in manufacture. The laser's value in telecommunications, for example, relied upon sufficiently high quality and cheap optical fibres, which did not occur until some time later [906]. This dependence can be finely attuned – whether a given technology becomes pervasive can depend critically upon small price movements of underpinning technologies. It is not sufficient to consider a particular technology change – one needs to consider the change of the larger *technology system* [330,403]. Such changes are complex and can occur in many different ways [406]. The slowest changing part of a system often limits its speed of adoption and impact, a phenomenon known as a 'reverse salient', where 'components in a system … have fallen behind or are out of phase with the others' [256,508]. One example is the availability of sufficient capable memory systems in the development of computing [510]. A reverse salient can be a social rather than technological phenomenon, as is found in the public opposition to drinking recycled water. While the technological hurdles have been long solved, attitudes and behaviour can form a powerful reverse salient [799].

The time lag in assimilation of major innovations. Major innovations take a long time to assimilate. The evolution of past general purpose technologies shows that this is a general pattern [382,622]. This pattern can be expected to continue since it is driven by the speed of cultural and infrastructure change, which are usually slow. Such changes typically require changes to organisational structures and processes [241,278]. Management structures and technological systems mutually reinforce each other, and thus the slow-changing nature of management structures also slows technology change [115,508]. This has been empirically demonstrated with software technologies [637], where it is known as Conway's law, which states that software artefacts reflect the structure of the organisation that produced them [207]. This interdependence between technology and organisational structure is a major cause of lag in adopting new technologies.

Envisaging a completely new system. However hard it is to envisage a new technology, it is harder still to envisage a new system. New systems are what lead to major social changes (the electricity distribution system, for example, or the system of roads designed for pervasive private motorised vehicles). Many technological components owe their initial existence to current systems, but eventually they shape and *become* the system. In the 1830s, for example, railways were envisaged in the US merely as feeders to the existing canal system, but they later surpassed the canal system forming their own railway system [375,910].

Forecasts depend upon interest. Proponents of new technologies have an interest in exaggerating the possibilities of the technologies (Section 2.4, 2.8). Conversely, those benefitting from existing technologies have an interest in arguing for the status quo [706], see also Section 2.7, Appendix C.2[930])

Cognitive biases have a substantial impact on prediction (Sections 5.2.4, 6.4.2, [437,547,1058]. The way people think about events in the far future differs from the way they think of those in the near future. Distant future scenarios are imagined abstractly and with less concrete detail than scenarios set in the present or near future. This explains why future scenarios often turn out in hindsight to be flat and lifeless. There are further common biases and self-deceptions that need to be recognised in forecasting [1057]:

- The way people view past predictions is prone to *hindsight bias* or the 'we knew it all along' effect [1151].
- *Optimism bias* or unrealistic optimism – the tendency to underestimate risk and over estimate benefit – affects the prediction of new technologies in several respects, but especially in assessing rates of adoption (Sections 5.2.4, 6.4.2).
- *The representativeness heuristic* is used when making judgments about the probability of an event under uncertainty. When people rely on representativeness to make

judgments, they are likely to judge incorrectly because the fact that something is more representative does not actually make it more likely [1067]. Representativeness will bias technological predictions to favour the familiar [549].

- *Survivorship bias* the tendency to concentrate on the survivors of a process and inadvertently overlook those that did not. This bias plays a substantial role in prediction as 'a stupid decision that works out well becomes a brilliant decision in hindsight'. This is why merely asking 'successful' businessmen or technologists what to do is a mistake; a lot of their success is due to luck[32]. Attempts to find the recipe for technological success will likely suffer the same fate as the attempt to find successful companies. Just because you are doing well now, it is not necessarily because of what you did, and there is no certainty you will continue to do well [830]. Looking at failures is much more instructive (Section 7.5).

Another major problem for technological forecasting is the uncertainty of technological change (Section 2.9.1) and the difficulty people have in dealing with uncertainty (Sections 5.2, 6.4.2), especially with regard to forecasting [545]. The phenomenon of feeling certain when one is not and the inability to acknowledge failed forecasts affects technological forecasts [153,355,1031].

Because of the uncertainties involved in future technology prediction, one needs to take care in considering the accuracy of past technology predictions. It is easy, when considering past (and somewhat fantastic) predictions either to cherry pick the apparently prescient predictions, or to make fun of those that were utterly wrong [957]. Nobody has managed to consistently predict future technologies well, and even some of the wildest predictions have come to pass in certain respects. Measured and scholarly retrospective analyses reinforce the complexity and unreliability of technological prediction, but also illustrate that aspects are predictable [192,604,843].

3.5 Technology predictions

Technology prediction is indeed difficult (as explained in previous sections) but it is possible to make *some* predictions of future technologies that will have a large impact on Australia. This section does so at three different levels:

- The prediction of particular technologies, which is possible over a sufficiently small time-horizon (Section 3.5.1);
- The prediction of general-purpose technologies. These are also the safest predictions to make and are readily amenable to policy interventions (Section 3.5.2);
- The prediction of general features of technology and technological change that can be expected to persist (Section 3.5.3), which are often actionable in developing policy.

Viewing technologies as arrangements of components explains how certain elements of technological change seem remarkably well predictable, but other aspects are not (Sections 1.2

[32] The point is nicely illustrated by the famous story about Enrico Fermi and the great generals:

> 'As to the influence and genius of great generals — there is a story that Enrico Fermi once asked Gen. Leslie Groves how many generals might be called 'great.' Groves said about three out of every 100. Fermi asked how a general qualified for the adjective, and Groves replied that any general who had won five major battles in a row might safely be called great. This was in the middle of World War II. Well, then, said Fermi, considering that the opposing forces in most theaters of operation are roughly equal, the odds are one of two that a general will win a battle, one of four that he will win two battles in a row, one of eight for three, one of sixteen for four, one of thirty-two for five. 'So you are right, general, about three out of every 100. Mathematical probability, not genius.'' [557]. See also [561].

and 2.5). Prediction of technological change is an estimate of what the technological rearrangement might be, that is, how the various parts will be combined in different ways. The prediction of minor changes is conceptually simple – everything else remains the same, and some small component varies for example nickel metal-hydride batteries are replaced by lithium-ion batteries in mobile phones. The impact of these changes can seem small when looked at in isolation, but they can cumulatively have a huge impact. For example, the gradual improvements in the cost of producing batteries for household storage of electricity does not create 'radically new' technology. But when (the timing being also hard to predict) the cost of the technology is competitive, there will likely be widespread adoption along with concomitant impacts on the electricity market and distribution networks (overcoming the 'electrical despotism[33]' of the current centrally controlled grid). The sorts of technological change that cause large impact are those which overturn entire systems (another example is the replacement of physical stores by online stores which is likely to be as disruptive in the long term as was the replacement of small local stores by supermarkets [832]). These transformational changes will always be very difficult to predict because of the dependence upon so many exogenous factors.

3.5.1 Predictions of particular future technologies

The difficulties of predicting impacts of existing and new cutting edge technologies can be illustrated with a few examples. These are deliberately chosen to be specific, potentially transformative, but with the current state of knowledge, highly uncertain.

It would be reckless to pronounce definitively about (for example) the technological prospects of the recently discovered orbital angular momentum of light [19,26], or radio-waves [1039], which is a component of the angular momentum of light that depends on the spatial profile of the light intensity and phase (distinct from the spin contribution due to polarisation). The orbital angular momentum of light *might* serve as the basis of radically increased bandwidth for telecommunications systems based on optical fibres [133] or free-space radio waves (demonstrated over a very short distance recently [1154]), in which case it would have huge impact; or it might forever remain a laboratory curiosity. It is impossible to say now which of these predictions will come to pass [808]. As seems to be often the case with new technologies, even the underpinning scientific principle (far-field free-space radio transmissions) has been questioned [568].

It is equally risky to accurately predict the impact of, for example, nanomaterials [872] or nanomedicine [701]. With these, or any new scientific and technological advances, a large impact *might* be just around the corner. However, like quantum computing [768], there *might* be decades of frustration while engineers attempt to make a system work [2]. It *might* also end in failure in the same way that designers of 19th century mechanical computers were ultimately defeated by friction [1012]. Aaronson said, 'Like almost all current quantum computing experiments, this currently has the status of a fun demonstration proof of concept, rather than anything that's directly useful yet' (quoted in [182]).

In order to make predictions with adequate reliability, one needs to use *broader* categorisations of technology, and predict over a *shorter* time scale. Where there are simple-to-quantify empirical regularities regarding the performance of technology (as outlined above in Section 3.3.7), one can confidently predict these will continue for the medium term. But the *impact* of such continued progress is much harder to predict, because it depends upon so many other factors. Nevertheless, businesses will wisely place bets predicated on such predictions – for example the ongoing regular diminution of the costs of photovoltaic panels (see Figure 7) and

[33] So called 'hydraulic despotism' whereby a central agency which controls access to water resources in a monopolistic manner has historically had a large influence on the development of societies [1140].

batteries will offer opportunities for developers and integrators of such systems and cause problems for existing energy supply monopolies.

Possible impacts of current and near-future technologies are described in the answer to project question Q1 (page xii) and in the working paper *Future Technologies Overview* [343]. The report does not assert that these are going to be accurate predictions; they should be used with caution in the development of policies and interventions; see Section 7.6 for how to develop policies in the light of uncertainty.

The working paper is summarised below in the form of the following stylised facts:

- Computing and data technologies will continue to improve (data storage, transmission and processing speed). There will be continued advances in algorithms which will gradually enable computers to do more 'intelligent' tasks (for example a car that can autonomously drive on roads, and not just automatically control the speed, stay in lane, navigate, prevent the brakes from locking, optimise the engine operating parameters, and manage the maintenance of the car, as is done now).
- DNA sequencing and related informational biology technologies will continue to get cheaper, but merely obtaining genetic sequences cheaply does not solve all medical problems (e.g. there remains the need to analyse and store all the data so obtained). This continued reduction in price will likely allow for greater personalisation of medicine and industrialisation of biology [213].
- There will likely be cheaper and better 3D printing, including 3D printing of biological materials [541], which will likely change the economics of mass-manufacturing versus bespoke / personalised manufacturing.
- Renewable energy generation and their associated storage, prediction and management technologies will continue to improve in reliability, performance and price.
- It will be possible to partially describe future technologies in terms of 'convergences' – a way of understanding the fluidity and merging of categories, but also an illustration that problems do not fit those boundaries. This classificatory variability is hardly surprising – it even occurs in biology [536]. Examples include:
    - Computing power + analytics + networking = automation of brain work
    - Computing power + robotics = further automation of manual work
    - Autonomous cars + sensing + networks = safe personalised (public) transport
    - Renewable energy sources + sensing + networking + analytics + extensive distributed energy sources = green power (smart grid)
    - Fast DNA sequencing + analytics = personalised medicine
    - Extensive sensing + analytics + networks + autonomous vehicles = safe, green, sustainable (smart) cities along with wide scale surveillance of human activities
    - Nano-technology + analytics + RFID technology = automatic food quality monitoring, body function monitoring
    - Meso-scale modelling and simulation + low cost high performance computing = new era in real-time decision making

3.5.2 Prediction of existing and new general-purpose technologies

The higher the level of aggregation used, the less likely one is to have one's prediction falsified by the facts. A middle ground, which also leads to actionable insights, is the prediction of future general-purpose technologies (which themselves are at different levels of aggregation – for example machine learning is a particular Information and Communications Technology). It is still important to recognise that hindsight can give the impression of inevitability and make one overestimate the accuracy of foresight that is possible:

> Viewed in retrospect, the evolutionary path of a fully developed general-purpose technology has the appearance of inevitability. When the technology is in its infancy, however, an observer looking into the future cannot conceivably know if it will turn out to be a modest advance operating over a limited range, a general purpose technologies, or anything in between [621] (page 48.).

Noting that the classification of general-purpose technologies suffers from the classificatory slipperiness of any technology, this report provides a list of current and potential general-purpose technologies that are likely to substantially affect Australia. These include[34]

- Electricity infrastructure and energy generation, especially low-carbon energy technologies including, solar, wind and new nuclear technologies [9,596] ;
- Energy storage [930];
- Motorised vehicles; aircraft; interchangeable parts and modularity; new forms of industrial organisation (e.g. lean production);
- Nanotechnology [585,619];
- Biotechnology, especially genetic technologies, including GM crops [769];
- Additive manufacturing (3D printing) [540] including bioprinting [1110];
- New materials [441];
- Waste disposal and recycling technologies [272];
- Agriculture and food technologies [362].

The most general and pervasive technology now, and in the foreseeable future, is ICT (Information and Communications Technology). Information, communications and control is central to almost every human activity, and there is no reason to expect that the central role ICT has had historically will change [102]. In addition to the obvious manifestations (including broadband internet [785], data storage, telecommunications, machine learning [229], robotics, autonomous systems), ICT, especially technologies for data [306] will enable the 'datafication' of almost every other industry and technology [657]. While data analytics in particular does create new industries (e.g. computational advertising [414] and its ancillary services such as computationally enable social networking), its impact is hardly limited to that, as some prominent pessimists erroneously believe [438]. Data analytics is already transforming industries such as

- Manufacturing [518];
- Transport [1];
- Retail (e.g. through improved demand forecasting) [287];
- Materials [212];
- Law [318] and law enforcement [829];
- Biology, facilitating the industrialisation of biology [213];
- Agriculture [320];
- Energy –prediction of the output of renewables such as solar and wind, and in 'smart grid management';
- Medicine – bioinformatics leading to personalised medicine; use of data analytics in health care to learn better practices;
- Education – through fine grained analytics to improve teaching [1075].

The above list could be extended indefinitely because of the simple fact that any existing industry has data of sorts embedded in it, and data analytics can unlock the value of that data,

[34] See the various technology forecasting reports cited in Footnote 24 and [621,622] for more examples of GPTs with large current and future impact.

and consequently transform the industry [643]. These industry transformations will continue and be one of the major drivers of technological change in Australia in the foreseeable future.

The identification of GPTs with pervasive impact (especially ICT) is central to policy responses to future technological change. As with any other new technology, to derive the greatest benefit, Australia needs to invest in the development of the skills necessary to invent, adopt and use these GPTs. General Purpose Technologies, especially ICT, are suitable foci for government sponsorship of R&D precisely because of the generality of effect and impact. These interventions are covered in Chapter 7.

Beyond such broad-brush predictions, this report predicts that there will be some technologies with more general uses than others, and that their future histories will mimic those of the past. They will do so in diverse applications, with broad impact, at different timescales of adoption (ultimately long timescales). These technologies will reshape whole sections of society, enable other new technologies, rely heavily on other technologies, and be resisted strongly by some because of their revolutionary impact.

Whereas specific predictions about the future impact of technologies are rarely accurate and precise, general patterns of technology change are more stable, and importantly, they can provide guidance to governments. These general patterns are addressed next.

3.5.3 General features of technology change will persist

Although the future impacts of particular technologies are impossible to predict with accuracy, there are many general features of technological change that will persist [382,823]. The following predictable features of technological change, although multiple, complex and overlapping, will continue:

New technologies that have large economic impact will be based upon basic research and thus need government support to promote technology collaboration and commercialisation opportunities (Section 7.9).

- New technologies will arise from the creative recombination of existing technologies.
- The large-scale economic impact of a new technology will take a long time, and for 'general purpose technologies' will typically take several decades [221,241].
- New technologies will not create a total revolution [210]. For example, it will not be the case that: all cars are entirely autonomous; unmanned aerial vehicles will entirely replace road vehicles for freight transport; or artificially intelligent robots will take over the world.
- New technologies will not completely 'solve' the problems they are designed to fix – they will partially solve problems, and will also often introduce new problems.
- New technologies will come into the world imperfect; there will be failures; some people will conclude the technology is intrinsically bad or unworkable, but often the bugs will be ironed out and the technology will eventually thrive.
- New technologies will be developed by people for the thrill of inventing as well as for a specific purpose.

Technologies will continue to change in an evolutionary manner (Section 2.3). Some existing industries and businesses will adapt to new technologies and thrive; others will go out of business. Fast adaptation will continue to be a competitive advantage (Section 4.3.1, [299,303,705]).

- A tension between early and late lock-in will remain due to path dependence caused, among other things by increasing returns, virtuous circles and other positive feedback mechanisms [245].

- Adaptation of technologies developed for one purpose to solve different problems will continue [392].
- The pace of technological progress will remain gradual in general, with periods of rapid change [297,704], (Section 2.1).
- There will remain a trade-off between short-term optimality and long term adaptability, which points to the benefits of designing technology for adaptability.

Radical technological change will continue to come from many sources including users outside the apparent field [533,597,908,1102]. As van der Poel says:

> Because outsiders do not share the current technological regime, they may well initiate radical innovations that depart from that regime. They think differently ... Such radical innovations can result in the transformation of a technological regime and, thus, in new patterns of technical development [1085].

Examples of inventions with profound effects that are usually ascribed to an outsider include the telephone (Bell, a professor of elocution), the electric light and power system (Edison), the steam turbine (Charles Parsons and Karl Gustaf Patrik de Laval), the aeroplane (the Wright brothers, bicycle mechanics), the gyrocompass guidance and control system (Anschiitz-Kaempfe and Sperry), the dirigible (Zeppelin) and the jet engine (Whittle, trained as an aircraft mechanic and then pilot).

In a similar way, new technologies will be developed by 'non-experts':

> Carriage makers played a negligible role in the development of the automobile; makers of stagecoaches played no role in the development of the steam locomotive who in turn showed no interest in the diesel locomotive; manufacturers of piston-driven aircraft did not become leaders in jet engines; the dominant makers of vacuum tubes did not become the dominant players with transistors; nylon was not developed by experts in silk; and the telegraph company (Western Union) saw no value in the telephone [908]; (see also [183]).

Firms will continue to learn-by-doing through continuous interactive learning and technological advances and adoption will occur most rapidly where skills are most advanced [216,483,529,1043]. This will manifest itself by continued strong geographic clustering of technology adoption.

Large social problems will be addressed and solved (sometimes only in part) by new technologies. For example, energy production will continue to be decarbonised – worldwide, the carbon emissions per unit energy production have reduced by 0.3% per year since 1850, although of course with substantial increase in total energy produced, total carbon pollution has risen. The problem of carbon pollution needs solving, and is technologically solvable, albeit with system delays (technological inertia) [454].

The usual sources of technological inertia will remain due to the reaction of vested interests and the need for related systems and infrastructure to adapt [706]. At the firm level there will remain substantial 'stickiness' – persisting with inferior technologies when superior technologies are readily available [299].

Convergence of classes of technologies will continue – this is a side-effect of classificatory change and gradual evolution, rather than a feature in itself[35]. Technologies will converge through

[35] Confer the non-sequitur 'given the convergence of technologies and our small scale in the face of intense global competition, it is necessary that national policies be coordinated in several dimensions: across technologies, across application areas and across the national and the state governments.' [964] –

technological interdependence, innovative combinations, new ideas coming from outside, and through the impact of general purpose technologies in transforming existing industries. Another meaning of convergence arises when industries that produce different goods make use of the same production technologies [913].

Divergence of classes of technologies will continue – this is the flip-side of 'convergence'. Technologies that at one point are lumped together will split into what later become distinct technologies in the same way that electrical technologies first split into heavy versus light current; hardware vs. software; software vs. digital content; digital content vs. electronic games; electronic games vs. networked immersive online multiplayer games – all of which have diverged considerably from the design of electrical power systems.

Attitudes and meaning will always play a role in how people choose to adopt and use technology e.g. fashion waves, status, risk judgement (Sections 5.1, 5.2).

- Hype will persist – the impacts of current technologies will be overestimated in the short term (and often underestimated in the long term).
- Technologies will continue to be aggregated in different ways.
- People will say change is happening faster (or slower) now than in the past.
- People will overestimate their ability to accurately predict.
- There will be lots of one-true-cause explanations of change.
- It will be (erroneously) believed that it is necessary to accurately predict future technologies in order to determine good policy with regard to technology.
- The singularitarians will not admit they are wrong when the 'singularity' does not arrive in 2038. Like the Seventh-day Adventists described in [355], they will keep their religion going without the predicted divine appearance.

Some other patterns of technological change that will persist are:

- Small technological changes will sometimes lead to radical effects ('architectural change') [484]. The architecture of new technologies will shape the structure of organisations and vice versa (refer to Conway's Law in Section 3.4.1) and this will remain one of the reasons for institutional inertia in the face of technological change.
- 'System innovations' enabled by new technologies will have large effects. The technology change might be relatively small – decreasing price per byte of digital storage, for example – but the impact can be huge – music shifting to online sales and storage on ipods, for example [403].
- Reverse salients [511] will recur which will slow down system transitions [403].
- Gateway technologies and modularity enhancers will continue to play a substantial role (Section 7.7.6).

3.6 Reframing the prediction of future technologies and their impact

The prediction of future technology is complex. The difficulties of predicting future technology are primarily due to the uncertainty of technology change (Section 3.4.1). Given the limitations of predicting technology change, what can one do? In this section the report offers three suggestions:

1) *Learn from the past* as both a guide to the future but also as a way of understanding the limits of predictability of future technologies and their impact.

---

the 'necessity' is not demonstrated in any way. The historical record shows the contrary – it is many independent actors loosely controlled that seem to be able to adapt and respond to change best [915].

2) *Predict solutions of problems* not applications of particular technologies.
3) *Use predictions as a spur to invention* and in encouraging invention take account of the implications of uncertainty.

3.6.1 Learn from the past

> As we anxiously ponder our destiny on the eve of the twenty-first century, striving to understand and manage technologies of fearful complexity and danger, an understanding of how people in the past thought about technology and the future may provide useful insights and even a modicum of humility – Joseph Corn [210].

There are three reasons why prediction of future technologies needs to learn from the past:

1) Technology change takes time – the largest impacts felt now are not from technologies developed a couple of years ago, but those reaching back decades, centuries and even millennia [321]. The time lag is larger for the more radical and impactful technologies [221,382,622] (Section 2.2). New technologies build upon and adapt the old. The process depends on timing, on the parts-assembly nature of technology, and on self-fulfilling prophecies to retain the momentum of empirical regularities. Merely looking at the 'new' at a single point in time misses most of the story.
2) Understanding and remembering previous failed predictions is vital in preventing overconfident assessments today (Section 3.4) [604]. Such understanding might help counter the dominant sentiment that 'to be popular at all when writing about science and technology almost required that one be upbeat and prophetic' [210]. Backcasting techniques (retrospective analyses) can highlight the potential, feasibility and impacts of other technologies, thus shifting the focus from prediction to feasibility and choice [891].
3) Study of the past can reveal recurring features of technological change that are likely to persist in future (Section 3.5.3).

Achieving respect for the past requires knowledge of the past. Within Australia there are very few courses at university level on the history of technology,[36] and almost no engineering students encounter technological history in any depth during their studies. Given the substantial role that technological advance has played in the development of Australia and its central importance for further development, it is remarkable that so little attention is given in Australian universities to educating future graduates about the complexities and patterns of technological change.

3.6.2 Predict solutions of problems not applications of particular technologies

A response to the difficulty of accurate prediction of future technologies and their impact is to work 'backwards' from the problem i.e. work out the desired end state, and then work

---

[36] The few current Australian courses or majors offered in this area seem to be:

- One major (comprising several courses, but none specifically on the history of *technology*) at the University of Wollongong.
- One course offered by the Arts faculty of the University of New South Wales.
- One course in the School of Education at Southern Cross University.
- One course offered by the School of Media and Communication at RMIT University and one course offered by the School of Humanities at Griffith University – these are not so much histories of technology but histories of the impact of particular communication technologies.
- There is (apparently) only one course offered in Australia as part of an engineering degree at the University of Sydney.

Undoubtedly students meet the history of technology in small parts within broader courses. However, given its importance, it is surprising that it seems to primarily be taught at that small and incidental scale, rather than as a systematic topic within its own right which can substantially aid graduates in their future careers, whether they are technologists or not.

backwards to determine how it might be solved rather than starting with a technology, and predicting forwards what its impact might be.

This is the approach adopted by Gilfillan in the 1937 report by the US National Resources Committee [522,745] (Section 3.4). This is a particularly useful method for prediction, given that any one problem can be solved (or partially solved) by many different inventions/innovations, and there are many solutions to any given design problem [15,147,422]. This problem-oriented perspective was support by a series of retrospective technology assessments done in the 1970s [422]. 'Technology assessment should take a broader, problem-oriented perspective rather than focussing on specific technologies' [604].

It is reasonable to expect that many problems will be solved with technology. But one cannot have any certainty about which technology and when. Successful widespread use typically relies upon other technologies and infrastructure. For example, the laser's value in telecommunications relied upon sufficiently high quality and cheap optical fibres, which did not come till some time later. This technological dependence is pervasive and widespread – *every* new technology depends upon a wide range of other technologies, whether in operation or in manufacture [906]. This dependence can be fine-grained, whether a given technology becomes pervasive can depend critically upon small price movements of underpinning technologies. It is not sufficient to consider a particular technology change. One needs to consider the change of the larger technology system [330,403]. Such changes are complex and can occur in many different ways [406]. It is often the slowest changing part of a system that limits the speed of adoption and impact (see Section 2.1).

Gilfillan's principle of equivalent invention (many inventions can solve the same problem), can actually make prediction easier. As he later explained, this allowed him to correctly predict in 1937 that a means would be found to land aeroplanes in fog [422,745]. His logic in 1937 was that this was a problem that society cared significantly about; that there were many possible ways it could be solved (he listed 25 possible different means); and that at least one of these would likely succeed in the market eventually. He did not attempt to predict which solution, or exactly when it would occur, or what it would cost.

Contrast the above prediction by Gilfillan with his prediction that television would be three-dimensional within 10-15 years (prototypes of this technology were in existence already in 1928). In contrast to the solution of a problem, this was much closer to a prediction of an impact of a (then new) technology. As it turns out, it is only now that 3D television is starting to be used, and it is likely to be some time yet before it is widely adopted, if ever [87,89]. The reasons for its slow take-up are not technical, nor are they market-related (one can buy well-functioning 3D television receivers cheaply now). But it seems that not many people *want* 3D television[37], it thus lacks social acceptability. Prediction of pervasive uptake implies prediction of social acceptance, which is one of the hardest things to predict.

Working 'backwards' from the problem may be useful when attempting to predict the future, but it alone does not solve the problem of motivating and managing technological development. Technologists are often inspired by intrinsic reasons, not by intrinsic ones (Section 7.3). Furthermore, investment in technological R&D is better served by focussing on the technological capability (Section 7.9). Nevertheless, for the purpose of future prediction it is helpful to look at the problems to be solved, these can take the form of national research priorities, or more specific tasks.

---

[37] The BBC is 'to suspend 3D programming for an indefinite period due to a 'lack of public appetite' for the technology'. The Sports network ESPN also closed its 3D sports channel in 2013 because of lack of uptake [86,88].

The Commonwealth Science Council strongly supports creating national science and research priorities with a focus on the practical challenges facing Australia [180]. This approach highlights the importance of taking a broad problem-based perspective and emphasises the need for cross-disciplinary research when seeking innovative solutions. The top-level priorities are as follows:

Food. Optimising food and fibre production and processing; agricultural productivity and supply chains within Australia and global markets.

Soil and Water. Improving the use of soils and water resources, both terrestrial and marine.

Transport. Boosting Australian transportation: securing capability and capacity to move essential commodities; alternative fuels; lowering emissions.

Cybersecurity. Improving cybersecurity for individuals, businesses, government and the national infrastructure.

Energy and Resources. Supporting the development of reliable, low cost, sustainable energy supplies and enhancing the long-term viability of Australia's resources industries.

Manufacturing. Supporting the development of high value and innovative manufacturing industries in Australia.

Environmental Change. Mitigating, managing or adapting to changes in the environment.

Health. Improving the health outcomes for all Australians [180].

There is of course no way one can predict accurately when or how such problems will be solved (and they need to be stated in much more concrete terms to be falsifiable). And there is a danger in viewing these challenges in too narrow a fashion; typically one can expect the major advances will come from "outside" the given sector. For example, setting aside cybersecurity, which is obviously a data technology problem, none of the others *superficially* necessitate data technologies for their solution. However, if there was a single broad class of technology that perhaps stands to offer the greatest progress against all such problems it is data technologies, especially data analytics [657] [643], which stand to transform traditional sectors or classes of problems such as

- **Food production** – through fine-grained monitoring and analytics.
- **Soil and water** – for example groundwater modelling and mapping.
- **Transport** – analytical view of all national freight movements, offering the opportunity for optimisation of the system; predictive variable road pricing to reduce demand; fine-grained analytics to support the making of transport investment decisions; mechanism design to control demand; modelling and simulation of entire transport systems.
- **Energy and resources** – For example smart grids, energy markets, prediction of variable renewable energies such as wind and solar to complement the already pervasive prediction of demand.
- **Manufacturing** – underpins use of additive manufacturing, agile supply chains, modelling and simulation technologies [305], and data analytics in materials design [212].
- **Environmental change** – monitoring, sensing, modelling, enablement of citizen science
- **Health** – personalised medicine, NLP for nursing handover, bioinformatics, ICT-enabled delivery of health services, industrialisation of biological experimentation [213].

Of course other technologies from 'outside' could also have a major impact. Data analytics has the most promise at present.

3.6.3 'The best way to predict the future is to invent it'[38]

As illustrated in the introduction of this chapter, predictions need not be accurate in order to inspire (and as elucidated in Chapter 7, imperfect prediction is no barrier to rational policy setting). Focusing on the inspirational aspect is perhaps more valuable than trying to make precise forecasts. When combined with the problem-orientation this can serve to inspire technological advance (Section 3.3.1).

Scenarios offer a range of options of what the future might hold 'to find out about possible futures that lie ahead; to single out the more desirable ones among them; and to invent the instrumentalities for the deliberate pursuit.' [480].

Inspirational visions can counteract the pessimistic view that the world has many problems and that they cannot be fixed:

> Noting the success of the foresight workshops in building more positive visions of the future amongst mid secondary school students, it is recommended that: Australian Governments provide opportunities for students in mid secondary school to experience the ways in which the technique of foresight can encourage the development of more positive and engaging visions of the future as well as an attitude which enables young people to manage their role in the future [53].

But this does not go far enough – students also need to learn how to go about inventing the future that they envision (see Sections 7.3, 7.6.2). The most powerful skill development that can be offered is not technology specific – it is the skill to change, to do new things, to adapt. It is the skill to invent, adapt, adopt and exapt new technologies. This requires a cultural shift at all levels – from school students being willing to try developing technologies (and learning how to fail) to managers and leaders learning that their inability to predict, control, categorise, order and organise the chaotic and evolutionary nature of new technologies is not a cause for resistance and recalcitrance, but rather should be one of facilitation and enablement.

3.7 Envisioning the technological future

Prediction is useful for several reasons:

- Prediction assists industry and users make decisions regarding the adoption of new technologies. Prediction can spur action; aid planning; aid policy development and aid investment decisions.
- Prediction can serve as an inspiration to technology development – many technologies that now exist do so because their inventors were inspired by predictions – a productive self-fulfilling prophecy
- Optimistic technological foresight can encourage the development of more positive and engaging visions of the future as well as an attitude that enables young people to manage their role in the future.

The prediction of new technologies is very difficult, largely because of how technology evolves – a given technology depends upon many others; its impact depends upon the larger environment (Section 2.3). To predict a single technology well thus requires a much broader prediction which is impossible. Furthermore, impact depends upon attitudes and beliefs (Chapter 5.1, 5.2) which are even harder to predict.

One can accurately predict narrow technological improvements on sufficiently short time scales (and thus make short term investment decisions based on such predictions); but one cannot predict the larger impact of a given technology, and thus long term investment (especially

[38] Attributed to Alan Kay in 1971 [865].

technological research) needs to be more an 'act of faith'. One can predict that general-purpose technologies will continue to have a pervasive and long-term impact, but not precisely what that will be. One can predict that social problems will be solved, but not when and how and by which technology. One can predict some general features of technological change that are likely to recur, and these general patterns lead to actionable insights. Given the strengths and limits of prediction, it is valuable to start with the future problem or likely use and work backwards, rather than starting with the technology and forecasting its impact.

Broad predictions about future technological change are possible. General purpose technologies, which have the largest effects, also take the longest time to have significant impact. The impacts of general purpose technologies are difficult to predict in detail.

Future general purpose technologies [970] will likely include data analytics, biotechnology, additive manufacturing, synthetic biology, nuclear power (especially if the new generation methods can be made to work well enough) and nanotechnology [622]. There will be some technologies a lot more general than others, and their future histories will mimic those of the past. They will have diverse applications, broad impact, different timescales but ultimately take a long time, reshape society, enable other new technologies, rely heavily on others, and be resisted strongly because of the revolutionary impact. Data analytics appears to have the greatest promise in terms of breadth and depth of transformative impact across all aspects of Australian society in the next decade.

Technologies are sometimes perceived to be autonomous [1136] but this is better explained as 'technological momentum':

> Technological systems, even after prolonged growth and consolidation, do not become autonomous; they acquire momentum. They have a mass of technical and organizational components; they possess direction, or goals; and they display a rate of growth suggesting velocity. A high level of momentum often causes observers to assume that a technological system has become autonomous. Mature systems have a quality that is analogous, therefore, to inertia of motion. The large mass of a technological system arises especially from the organizations and people committed by various interests to the system [508] (page 76).

Some general characteristics of technological change are predictable. Ignoring the componentisation of technology can be limiting to understanding, and thus limiting to their prediction. The interdependence of technologies and how a single technology often requires others to function, has predictable effects – improvements in one technology can lead to improvements in others; delayed improvement in one technology can delay improvement in others.

Technological inertia (the formation of a barrier to emerging technology due to the preferred current dominance of a widely adopted technology) comes from existing infrastructure and vested interests with the status quo. Moore's law and related hypotheses of technological progress will continue in the short to medium term, but all of them will eventually plateau.

Prediction of impact is much more difficult than extrapolating narrow numerical performance indices. Impacts are unpredictable in any detail when looking at a reasonable time into the future.

There are 'limitations of the expert'. Technological inertia contributes to expert limitations. As current businesses have already invested in the status quo because they are enjoying the present success of particular technologies the experts aligned with these businesses can fail to be sufficiently alert to new technologies or to customers' changing needs [183].

Our capacity to imagine and predict is limited by what we already know. Viewing new technologies in terms of the old can limit the understanding of technology, and thus limiting to the prediction of technology. Even more difficult is imagining the complete displacement of old, long-dominant technology and their larger systems. This reinforces the importance of creativity in envisaging and developing new technology.

The larger the number of diverse research efforts that are undertaken, the greater the chances that new and affordable technologies will be developed that provide better solutions to important problems. Conversely, investing only in things that are certain to provide a commercial return in the short-run will strongly reduce the chances of new, impactful technologies with large positive impacts for Australia. Historically, large technological impact has often come from bold and uncertain steps, and there is no evidence to suggest that this will change [300].

Ultimately the difficulty of predicting future technologies simply reflects that the technological future is open. There are many possible technological futures available to Australia, 'the fundamental thing is to choose' [382] (page 372).

4 The impacts of technology

Summary

Technology influences all aspects of society – it is the major source of economic growth and it shapes the way we live, work and play. Conversely, society influences the technologies that are developed and adopted.

The impacts of technology are differential – they are positive for some, negative for others and sometimes of no consequence: every technology has the potential to benefit or harm.

Impacts of technology can be overdetermined; a given effect may have multiple causes.

It is difficult to predict technology of the future or what the impacts will be, the key is to respond to this uncertainty with speed, adaptability and transparency.

The impacts of technology are dependent upon, and particular to, context, time and place. Further the impacts are difficult to assess, and to ascribe causal influence.

Evaluating technology may not prevent all undesired impacts but it will help develop better a plan to respond to technological change.

Technology development has been one of the principal drivers of economic progress and social change through human history [703,711]. Change in and adoption of technology is the major source of industrial growth, consumption and productivity, and the uneven distribution of benefits across countries and regions over time.

Understanding the impacts of technology can help guide social, economic, and innovation policy, improve business practices and strategies, direct research, and is helpful in making a case for or against investment, construction, diffusion, adoption and regulation of technology.

4.1 Understanding impacts in an environment of complexity and interdependence

Impacts can be understood as things to assess and analyse in the past (crudely, 'retrodiction') or things to anticipate in the future (prediction): one may assess or evaluate the past consequences of a technology, product, or technical transition by attempting to determine its impacts (Chapter 6). Impacts can be framed in terms of costs and benefits. If one wants to compare outcomes, avoid or mitigate costs, or encourage benefits, one may attempt to predict the impacts of contemporary or future technology and the consequences of change or inertia (e.g. using cost-benefit or scenario analyses) (Chapter 3, Section 6.3). But this approach relies on many assumptions, and on unravelling the often confounding relationships between products, their precursors, and the technical, social, cultural, economic, security, democratic, and governance systems within which they are embedded, used, and changed (Section 4.4).

It is impossible to escape the impacts of technology, but often difficult to anticipate them in detail (Chapter 3). As observed elsewhere in this report, technological change causes economic and social change, and vice versa. Technology and innovation encourage and allow the movement of people, goods and services, as well as the generation and the further proliferation and transfer of technology and information, including scientific knowledge. That these are large-scale impacts of technology and innovation (construed broadly) is uncontroversial. However, it is difficult to predict, define, or measure the impacts of technology and technological change in detail accurately, not least because it can be some time after the widespread adoption of a product, process or system that impacts are observable, and they may be indirect. Furthermore, the outcomes of any technology or product are inevitably affected by its uses, other contemporaneous interventions (interdependence), as well as the product's history and the history of its uses (path dependence) [444,1076]. Even in the case of a pervasive technology such as the internet, while it is clear that its rise has been accompanied by considerable social, cultural, economic, and democratic change, both the broader impacts and the specifics of these changes are still emerging as the technology itself continues to change, and claims about these impacts are often highly contested (for some examples see Appendix 2: Case studies and [105,306,558,672,718,1013,1062]).

The challenge of understanding impacts of modern or future technologies can be better appreciated by looking backwards to the past as was done 50 years ago with a comparison of the space program and the railroad [385]. Any reader of this book, noting the contested and complex impacts of the railroad, will approach the assessment of the impacts of new technologies with renewed humility.

Another example is due to Ogburn and Gilfillan in 1933 who listed some 150 different social impacts of the radio. To make the point about the difficulty of distilling such impacts to a simpler story, they said

> the foregoing list is not summarized, as it is the detailed effects which should be noted. Even so, the items are not as detailed as they could be made. Each item might be broken down into other particular effects [792].

They do draw some general patterns of the effect of inventions (patterns of technological impact) which persist:

- An invention often has many effects spreading out like a fan.
- A social change often represents the combined contributions of many inventions.
- Inventional causes and social effects are intertwined in a process
- An invention has a series of effects following each other somewhat like the links of a chain.
- Groups of similar inventions have an appreciable social influence, where that of any particular one may be negligible.
- The accumulation of the influences of the smaller inventions is a significant part of the process.
- The majority of inventions are merely slight improvements on some existing device
- There are social factors as well as mechanical ones in social change
- Social factors in social changes are often derivatives, in part, from mechanical inventions, and vice versa.
- The effects of invention on society are of various degrees and kinds
- It takes time for the social influences of inventions to become fully felt.
- There are social inventions as well as mechanical ones, effective in social change [792] (pages 158-159).

Any technology or product will have many impacts, ranging from trivial to transformative; and a given impact is potentially the result of any of a number of technologies, their interactions, and their precursor technologies. Countless effects will also go largely unnoticed as they emerge, during the gradual and iterative processes of technological, social and economic change (Box 10), (Chapter 2). But cumulatively or over time these effects may amount to a significant impact. For these reasons outlined above – including time lag, indirect effects, path dependence, continuing evolution, complexity and interdependence – impacts are often unpredictable, overdetermined (an event or action is overdetermined if there are multiple sufficient causes for its occurrence) or indeterminable, even with hindsight.

What killed Maxine? Not quite a Just So story.
At the age of 50, Maxine was obese, with type 2 diabetes. Before she turned 65, she had died of a stroke. But just how much more complicated is her story? Maxine worked as a nurse. Often sleep-deprived due to shift work, she consumed a diet high in sugar and processed food. She was born in 1932 during the Depression, to a genteelly impoverished mother who may have been suffering from malnutrition, and her

father left when she was two, so she may have been malnourished herself. She reached adulthood in an era when cars were becoming increasingly affordable and processed food increasingly popular and cheap, drove to work and to church, watched a lot of television, smoked, and spent much of her life sitting down.

One of the fastest growing health problems in the world, the metabolic syndrome describes a set of disorders prevalent in Western populations and the urban developing world during the late 20th and early 21st centuries. These conditions include obesity, high blood glucose levels, high cholesterol and high blood pressure, impaired insulin regulation and body mass index changes. Metabolic syndrome will double your risk of cardiovascular disease, stroke, and type 2 diabetes, leading to higher morbidity and mortality than the general population [176,396,630,984]. The cluster of disorders is associated with a sedentary lifestyle and a high-fat, high-sugar diet, but also has epigenetic ('thrifty phenotype hypothesis') and genetic ('thrifty genotype hypothesis') origins [176,797,984,1113].

Swivelling chairs with castors began to appear in American workspaces from the mid-19th century as the collapse of distance allowed by the railway invited a change in business processes. Formerly family-operated businesses began to expand to the point that extra administrative staff were required, as well as places for them to sit. Functional concerns were at the forefront of design (including the use of castors and swivels), in order to maximise productivity and reduce the need for workers to leave their chairs, although it is not until the 1970s that ergonomic standards began to be a major consideration in the manufacture of office chairs [978]. Thus the inexorable advance of the railway contributed significantly to changed business practices, from which arose (or sat) a new professional class of clerical workers, who spent their days sitting down. The railway, and later the automobile, also contributed to changing settlement patterns and the geographic relationship between employment and domesticity, as this class of seated workers became a class of seated commuters as well.

Drafting tables, the precursor to the modern office desk, appeared toward the end of the eighteenth century [1035], although there are references to desks as objects for reading on as early as Chaucer's 'The Franklin's Tale'.39 The rise of typewriters in the 19th century, then word processors, and then word-processing software for personal computers, transformed government, business, retail, and hospital environments during the 20th century, including heavily influencing desk shape and work practices ([305,306]). The latest iteration of office 'seating' includes stand and sit-stand desks, as well as treadmill desks for active workers. These emerging office environments constructed themselves from this set of contemporaneous technologies, business needs, and social and economic contexts.

The railway also allowed for new food-distribution networks. At the same time, innovations in cropping, food processing and storage (including refrigeration) improved the access of the general population to calorie-dense and regularly available food. Today time-poor workers, stuck behind their desks for eight to ten hours a day and in their cars for several hours a week, eat calorie-dense snacks at work and processed food at home. Meanwhile, sitting at a desk for hours, texting on a mobile telephone, or browsing on a tablet or smartphone is associated with musculoskeletal pathologies including back and neck injury (see 'text neck', [465], headache, repetitive strain, and indeed with metabolic changes [107,814]. The changes to a person's centre of gravity associated with weight gain can increase pressure on her lumbar spine, further limiting mobility, in a vicious circle [465]. 'Sitting is the new smoking', as the recent saying goes [107,814]. But it turns out smoking may have been the 'new sitting' instead, given the rise in the second half of the 20th century of the cluster of disorders now described as the metabolic syndrome, with their associated increases in morbidity and mortality, giving credence to the claim that many of the impacts of technologies and their attending social transitions remain largely unnoticed until their cumulative effects become clearer in the long term.

The high incidence in Western and emerging economies of the metabolic syndrome did not arise in a vacuum. Social practices change in the face of emerging technologies, networks, and socio-economic systems. The nature of work and leisure shifts with settlement patterns change and commuting times. Freight transport adds to road congestion as it changes the cost and shape of food distribution. Social attitudes to food, exercise, weight, willpower, and people who are over or underweight in turn influence the ability of individuals to maintain a healthy lifestyle (for instance, recent research indicates that 'fat stigma' impedes long-term weight loss) [95]. In addition, the behaviours, environments, and technologies

---

39 "desk, *n.*" *OED Online*. Oxford University Press, September 2014.

of Maxine's ancestors (epigenetics), as well as their genetic and socioeconomic legacies, will play a role in her predisposition toward this cluster of disorders [955,984,1019].

Interventions which only target one or a few factors are unlikely to succeed in significantly reducing the incidence of the metabolic syndrome or its associated conditions like obesity and type 2 diabetes, because their origins are complex, multifactorial and interdependent. Analysis of the impacts of technologies and any attempts to mediate these impacts must take into account this complexity, recursion and inter-relatedness of social, economic, cultural, democratic, demographic, epidemiological, and environmental outcomes.

Box 10: What killed Maxine? Not quite a Just So story.

Despite the difficulty of predicting and describing impacts in detail, a broad understanding of the impacts of technology is important to improve intervention, mitigation and evaluation, and to understand and anticipate change:

- From the perspective of commercialisation, if investors lack any understanding of the likely commercial impacts of a potential product, they will not invest in it, and without such initial investment, the technology will never be introduced. At all points in the diffusion process, failure to identify potential impacts will impede uptake and adoption.
- The effects of any technology will be positive for some people, industries, sectors, or regions, catastrophic for others, and irrelevant for yet others.
- These effects may be direct or indirect, affecting household, local, regional, or even global economies, local or global environments, demographics, and security.
- How people understand the impacts of technologies may even affect the science and technology policy environment itself, as policymakers must respond to public opinion about perceived impacts [336].
- Public policy and technology adoption are determined by social and cultural values and contexts as well as by technological developments and the market, and in turn these policies affect social and cultural values, and technology.

Impacts of technologies may be unintended but predictable. For instance, one might anticipate that the increased calories across a population resulting from agricultural innovations during the Green Revolution would eventually lead to an increase in average weight as well as improved nutrition. In other cases, impacts may not be predicted, or predictable. For example, the metabolic effects of sitting down for long periods associated with the rise of the modern office could not have been foreseen previously because they required breakthroughs in the sciences of genetics and molecular biology. 'Intended consequences' will have negative impacts of their own (for instance, the improved speed and reach of travel afforded by the rise of the railway and motor vehicles eventually led to road congestion and long commuting times as they allowed a reconfiguration of urban, rural, professional, and domestic geography). Unintended impacts may be desirable in some contexts. For example, the faster calculation and processing speeds afforded by the first computers, initially designed to be bespoke research tools, led to a revolution in business processes, and eventually ushered in the digital age (see [305,306]).

New technologies are accompanied by assumptions and folklore. This is because changes which are associated with these new technologies may occur well before their medium to long-term effects are widely noticed, or can be assessed, other than by analogy with similar technologies. This means there will be a gap between adoption of a technology, the social and economic change it produces, and the creation of meaning (Chapter 5.1) [168]. Incomplete knowledge (and knowledge is always partial) may induce anxiety[40], paralysis, and emergent technophobia, or a gung-ho techno-solutionism which downplays negative impacts: the tension is between a desire for stasis and stability (e.g. fear of the negative impacts of change) and the desire for change in the search for improvement [649,849,850]).). In this environment of uncertainty, it is fruitful to recognise and account for 'necessary fallibility' [400]: in other words, how do policymakers, manufacturers, engineers, researchers, entrepreneurs, employees, and consumers of technology cope effectively with the fact that their knowledge is always constrained? While it is not possible reliably to predict how technologies will change, or what the specific effects of these transitions will be, nevertheless, change in technology will happen, and there will be consequences. The difficulty of anticipating these transitions and their effects with precision suggests the need for skilled strategists and workers with a nuanced, sophisticated and technically informed approach to technology and technological change (and their impacts), who can respond to uncertainty with transparency, speed, flexibility, and adaptability.

Managing perception of impact may be an important role for policy makers and strategists. Misjudging the tide of popular concern may affect the public administration of technology. It is worth having a public conversation about the impacts of technology, particularly in the context of security and existential threat. For example, historical context can show that while the internet may make Australians more or less secure, so the telephone, the postal service, the printing press, electrification, and mass transport were accompanied by insecurities, uncertainties, and unpredictable impacts. Information about rates of death and injury may provoke thoughtful questions about, for example, the threat of terrorism compared to the more banal existential risks people expose themselves to every day, like driving a car, having a bath, proximity to furniture, or drinking unpasteurised milk, and the freedoms Australians may and may not be willing to trade for increased security and safety.

One might suppose, given the path dependence of technologies (Section 2.7) that knowledge of the past can provide insight into the future, and it can. But even partial knowledge, or a correct guess, about the future will not necessarily prepare a company to respond adequately to that future (for example, Box 11). An effective way to overcome the difficulties of anticipation and attribution which can arise because of complexity and uncertainty (and which are identified above and elsewhere in the report) may be to reframe the problem: rather than asking 'What will the long-term future bring?', ask 'What actions and outcomes are likely to be consistent with my (my customers, my clients, my firm, my industry, my cultural, social, or political allies, my constituents, my nation, my descendants, humanity) long-term interest?' Not all companies or sectors will be in a position to adapt rapidly at every stage of their lifecycles. Agriculture and biotechnology, for example, often have very long lead times, and organisations with large fixed costs for plant equipment may be tied to contracts with suppliers in the short to medium term. But under conditions of uncertainty, strategies which can be adapted and evolve in response to new information, or which allow for adaptation, will perform better than strategies which assume an outcome and then seek to respond to it [605].

---

[40] Such anxiety is not new. For example the railroad strengthened family ties through better communication, while weakening them through increased mobility. To attempt to assess (for example) the influence of the railroad on family structure in some simple way (it makes it stronger or weaker) is as fraught, and ultimately pointless, as asking analogous questions to do (for example about the impact of computer mediated social networking tools on the family) [193].

Prediction, obsolescence and business failure

'Kodak has been obliterated by the creative destruction of a digital age… Five years ago, it was unthinkable that this American business legend would find itself in a bankruptcy position. Kodak was caught in a perfect storm of not only technological, but also social and economic change' [749].

Many commentators explained Eastman Kodak's decline as resulting from a series of poor planning decisions, a mistaken attempt to protect their film camera business and a failure to anticipate the rise of digital compact cameras. Contrary to the popular myth, page 10 of [295], the company did not fail to anticipate the popularity of digital cameras, but its business model was premised on selling cameras cheaply, with expensive but necessary add-ons in film and processing.
Kodak dominated photography for 100 years with a series of major innovations, controlling 90% of the US film market at its peak on some estimates [237]. The company filed for bankruptcy on 19 January 2012 as it 'finally succumbed to the digital revolution which left its products obsolete', and announcing it would no longer produce cameras but would focus on printers, Kodak ceased producing film in 2009 [749]. However, Kodak did not miss the digital revolution in photography, having assembled the first digital camera in 1975 [119]. The prototype's creator, Steve Sasson, called it 'film-less photography', and it could be viewed on a black and white television. The company patented various digital technologies, many of which most modern digital cameras incorporate (Kodak's intellectual property – primarily these digital patents – was estimated at $2 billion at the time it filed for bankruptcy) [806].

While the company produced some popular, affordable compact digital cameras, its baseline was affected by a fundamental change in consumer behaviour: casual photographers do not print digital photographs to nearly the extent that they printed analogue photographs, and Kodak made its money from printing, not from cameras. In 1975, Kodak employees invented a camera which produced photographs that could be shared on a screen. The critical change Kodak missed was not the change from film to digital: it was that the indirect effect of 'film-less photography' was 'print-less photographs'.

It is important to interrogate narratives of technological success and failure because the way they are framed influences how people behave, amplifying the impact of popular myths. This can lead to decision-making based on incorrect assumptions. As the camera components of smart phones improve, compact digital cameras themselves are gradually losing market share – consumers increasingly use their smart phones and associated apps to snap pictures and record video: 'Why have a compact camera when an 8 megapixels iPhone is almost as good and it's always there in your pocket?' [749]. In 1991, when Kodak produced its first commercially available compact digital camera, neither the company nor its commercial competitors predicted that within ten years, an entirely new product – a smartphone with inbuilt camera – would begin to dislodge the new technology, even as casual photography and digital photo-sharing experienced rapid growth.

Box 11: Prediction, obsolescence and business failure – a comparison of the fortunes of Kodak and Fuji.

4.2 Power, equality, disruption, and the impacts of technological progress

Technologies shift the balance of power, sometimes away from, sometimes toward, the powerful. This is because command of a new technology, or the means to produce or diffuse it, can create or reinforce power. The rise of movable type mechanical printing in Europe, and the invention of Gutenberg's printing press is often cited as a change in technology which may have shifted power, or at least the means of communication, towards the disenfranchised. A case in which a technical innovation shifted power toward the powerful, or at least was perceived to, would include the use of mechanical looms in the early 19th century. To illustrate the point that even such apparently clear-cut cases as these are complicated, Gutenberg's press was launched into an environment with an increasingly literate rising middle-class already hungry for books, which the previous laborious mode of production (copying by hand) failed to meet [326], and the shift away from the need for skilled hand weavers provided employment for unskilled workers.

The effects of technology are always mixed: beneficial outcomes for some, negative/malign for others, neutral or irrelevant to others. In addition, any widely adopted and pervasive technology will produce outcomes that have potential for widespread harm and for widespread improvement. When trying to understand impacts, it is important to consider:

- The impact/effect on whom? Impacts will always be uneven.
- That every technology contains potential for harm and potential for remedy.
- The metaphor of an arms race as an overarching driver of technology change. This report considers technologies' impacts via the motif of action, consequence, and response (i.e. a technological intervention is an action which has consequences. A new technological intervention may be a response to this impact, either to mitigate its effects, or to capitalise on them.

An impact may be understood as a disruption, but 'disruptive technology' is not a particularly helpful category. All technology is disruptive on some scale. For a technology to have a radical social or economic effect, many changes in other parts of the economy need to align with the right kinds of social and industrial practice [195]. No product is an island – 'disruptive technologies' could often better be described as successful parts-assembly projects (Bogost 2014) (Section 2.5). Companies such as Google and Apple, which have succeeded in producing and marketing ground-breaking products, have not so much invented new technologies wholesale, but have the knack of uniting researchers, technologies and marketers at the right time for them to have an effect and for their products to change social practices. Companies such as Uber and Airbnb are attempting to create new forms of social organisation as well as exploiting new technological systems: 'The implicit promise of buzzterms like "the sharing economy" is that technology … will fundamentally change the way humans relate to each other, on scales that are both mass and intimate'. Such aspirations have implications for notions of corporate responsibility and social capital in the promotion of new technologies (or in Uber's case, business models), in particular because perceived poor impacts for consumers can erode a company's social capital (the collective value of the social network related to the company) and undermine its social license (the level of acceptance within a community for a company to operate); see Uber's current media woes [393].

When technology is aggregated into broad categories (e.g. general purpose technologies), the impacts of technologies may be even harder to estimate precisely. General purpose technologies are pervasive socio-technological systems which are embodied in material objects, processes, and infrastructure (Box 12). Like many classifications, the term is a somewhat imprecise category (Section 1.1) – a transistor, for instance, is a general purpose technology and is a component of one, ICT. Electrical wires are a general purpose technology which are components of another general purpose technology, electrification. An automobile – a technology for transport – is made up of many components, including transistors and electrical wires. Like all general purpose technologies, cars are embedded in a socio-technological system which includes 'fuel supply lines, mechanisms for educating and licensing new drivers, companies to insure them, laws to govern how cars are used on common roads and police officers to enforce them' [60]. Because of their interconnectedness, interdependence, and ubiquity, as well as their (often) long lead times, it can be difficult to ascribe particular impacts to general purpose technologies, especially when it comes to calculating their economic effects, through measures such as productivity statistics. However, general purpose technologies are vectors for power and change [321].

General Purpose Technologies

Economist Richard Lipsey defines a general purpose technology as one which meets four criteria [622]:

1. It is a single, recognisable generic technology, which may be an object, process, or system.

For example, an automobile is, in a sense, an object, a process (driving, travelling), and embedded in a system.

2. Although it may not be widely used for some time after its invention, a general purpose technology becomes pervasive once the right set of social, economic and technical circumstances arises, and its importance should not be measured simply by its contemporaneous impact on productivity

Although available as a novelty luxury item from the 1890s, cars were not widely used until after the convergence of technical, industrial, economic, regulatory and behavioural changes which facilitated their large-scale production and adoption well into the second decade of the 20th century. Now they are ubiquitous personal transport in Western countries. The case of automobiles underscores another widespread impact of technology: the importance of facilitative infrastructures which arise in support, which can also engender or support other technologies (forming a socio-technological complex). The pervasiveness of motor cars is facilitated by significant investment in the socio-technical system in which they operate – roads, footpaths, streetlights, fuel infrastructure, manufacturers. Elements of this system – notably paved roads, and the expertise to make parts for early automobiles – predated the rise of the car, but did not foreshadow its arrival – in other words, the emergent system did not make automobiles inevitable. Nineteenth-century bicycle parts makers were involved in the first car manufacture, and roads were paved for a number of unrelated reasons, including for buggies, electric street cars, cyclists (who lobbied for paving), and public sanitation purposes (the laying of modern sewer systems [558].

Other elements of the system developed contemporaneously with motor cars, for example, regulatory systems, and yet others arose because of the existence of the car (for example, their contribution to the make-up of modern cities) – and are among the automobile's many important 'spillover effects', in Lipsey's terms.

3. It has many different potential uses

Motor vehicles are primarily used for transport, but Lipsey considers them to be a general purpose technology because of the great variety of products that can be transported.

4. It has many important long-term consequences (spillover effects), including economic transformation (chapter 2 change, chapter 3 prediction)

Other important spillovers of cars include the rise of freight transport, the collapse of distance, and the important economic effects of the many supporting industries associated with car use.

Box 12: General purpose technologies

There is a strongly deterministic flavour to conceiving of technology in terms of its impacts, effects or consequences (sometimes described as 'technological determinism' [976]. Furthermore, impacts are in most cases overdetermined: this is evident in tropes such as 'technological unemployment', which is as often due to wider socioeconomic changes as to the imposition of any particular new technique, process or product (Appendix C.7, [868]). However, it is certainly true, as Langdon Winner observed in 1997, that 'technologies are involved in changing the practices and patterns of everyday life' [1137] (Appendix 1: Understanding impacts) gives many 'changing practices and patterns' (although it is not by any means comprehensive). Given the ubiquity of technology, it is reasonable to suppose its impacts will be widespread, if not even. While it is not possible to predict reliably how technologies will change (except under certain very specific circumstances, see Chapter 3), or what the specific effects of these changes will be, nevertheless, technology will change. There will be resulting consequences, beneficial, detrimental, neutral, or all of these, depending on sector and circumstances, but there are some general things that occur as a result of technological change.

There are many different ways of thinking about the effects of new technologies, or changing technology. For example:

- How do technology choices and trends differently affect individuals, communities, industries, sectors, networks and economies?
- What are the effects of uptake on adopters and non-adopters?
- What are the effects of timing of adoption?
- What are economic and market effects?
- What are skills and employment effects?
- What are risks and uncertainties?

Rather than attempting the Sisyphean task of assembling fine-grained evidence for the panoply of impacts that exist, the report has instead distilled 29 stylised facts which capture many of the impacts of technology. (A stylised fact is a simplified presentation of an empirical finding which makes a broad generalisation, but will typically contain inaccuracies in the detail.) The implications of the impacts of technology for evaluation and intervention are addressed in Chapters 6 and 7.

4.3 The impacts of technology on Australia's social, cultural, democratic, economic and security systems

Australia's security, cultural, democratic, social and economic systems to a considerable degree are created and sustained by technologies. Australia is positioned in a wider region and an increasingly connected international system. Globalisation is a key impact of technology, with further ramifications for security, culture, democracy, governance, society and the economy. These stylised facts are grouped according to the systems which the project *Technology and Australia's future* was asked to consider – society, culture, democracy (and governance), economy and security – as well as some general impacts that apply across systems.

4.3.1 General impacts

1. Technology rarely has impacts that are unambiguously positive or negative. But neither are the impacts of technology ever neutral. Generally the impacts of technology are differential.
   a) Changes that are positive for some people or sectors are negative for others.
      - For example, products and processes that lead to improvements in manufacturing efficiency may improve company profits and a country's GDP, but will be accompanied by structural change that leads to occupational obsolescence.
      - Even change which is accompanied by widespread social and economic improvement brings losses for some people, and/or may change the distribution of incomes.

   b) A technological intervention may repair damage or improve outcomes from an earlier intervention, but will cause unanticipated harm of its own.
      - For example, the negative externalities caused by the ubiquity of horse-drawn transport, including but not limited to the problem of horse manure in city streets, was seemingly solved by the rise of bicycles, electric street cars, and automobiles, the last of which was 'cheaper to own and operate than a horse-drawn vehicle was proclaimed an 'environmental savior' [565]. Famously, the rise of automobiles has been accompanied by a slew of negative externalities of its own, including road congestion, air, water and greenhouse pollution, increased sedentarism, urban sprawl, land appropriated for roads, morbidity and mortality (although 'Per vehicle and per mile, it seems highly likely that the environmental problems caused by the horse were far greater than those of the modern car' and horses shared a number of the car's negative effects), page 9 of [663].

2. Following from 1.a) that changes can be positive for some and negative for others, impact on inequality, or disruption of a status quo, is an effect of technological change. This may be in the direction of greater equality or greater inequality, or both, depending on the context.

  a) Differential impacts of a technology may perpetuate and entrench inequality.
    - for example, the digital divide (inequality of access to, use of, or knowledge of ICT in a given population or between populations) may maintain socio-economic inequalities in a number of different ways:
      - People who are not digitally literate, which may include some elderly people, some new migrants, and others who for various reasons lack digital skills and education, will be unable to negotiate and capitalise on increasingly digitally-connected civic domains. As a result, they may have poorer access to government services and poorer job prospects, and may suffer social and economic exclusion.
      - People from lower socio-economic backgrounds may be less likely to have access to digital technologies for social, economic and geographical reasons. Even when access is available, they may not have the capacity to exploit digital resources, due to lack of awareness, training and knowledge.
      - Businesses located in areas with fast, reliable network connections will have a competitive advantage over businesses located in areas with poor or no connectivity.

  b) In other cases, a technological change or a regulatory intervention upon a technology may reduce economic or social inequality. For example:
    - Widespread availability of electronic media platforms promotes equality and diversity of information, improving access to information, to a means of evaluating it, and to diverse voices and opinions, compared to the dominant mid to late 20th century model of large media and publishing houses controlling the distribution of information (see [305,306]*)*.
    - There has been much emphasis on improving internet access via web accessibility, including through the Government 2.0 Taskforce. This effort is still a work in progress, and much of it predates the explosion in mobile and convergent media of the last five years. The development of guidelines and initiatives for these platforms should consider the opportunities technology may provide for improving social participation, work, education, and removing or reducing barriers.
    - Online education has the potential to reduce the cost of learning, opening opportunities for formal qualifications and teaching to students in lower socio-economic groups, and those for whom travel to, or distance from, a campus may be problematic (Appendix C.8, [764])
    - Economic scaling and process innovation bring down the cost of production, which in turn reduces prices, allowing access to people who previously could not afford products. The rapid rise in popularity and reduction in price of desktop personal computers during the 1980s is an example of the effects of economic scaling and process innovation. The wide availability and affordability of personal computers has improved people's digital literacy and opened whole new markets during the 21st century (see [305]).

Historically, the widespread adoption of mechanical production-line techniques in factories early in the 20th century meant more and better paid jobs for low-paid or unskilled workers (Appendix C.7, [868]). This employment shift contributed to the mid-century rise of middle-America.

3. Social, economic, and democratic change is as dependent on social engineering, policy settings, and existing socio-cultural context as on technology.

a) Regulation, consumer expectation, cultural preferences, public policies, and financial incentives including subsidies affect the potential market share and profitability of new products.
b) The effects of state and medical interventions into the choices of families and individuals (healthy eating and exercise campaigns, anti-smoking legislation, the assertion of public rights over pregnant bodies through the monitoring of the behaviour of expectant mothers, rules about school attendance, family welfare, child protection agencies etc.).

4. Following from 3, pervasive technologies are embedded within social, economic, and technological systems, which their existence has helped shape.
   - For example, the modern automobile ecosystem includes road systems (including roads, footpaths, traffic signals and signs, street lights, car parks), fuel supply, standards and processes for parts assembly, regulations (including licensing requirements and a network of road rules), conventions and enforcement systems, insurance, commuter-work regimes and housing patterns, and freight networks.

5. Existing technologies shape new technologies: the success of any product depends on a variety of circumstances being met, some of which can be anticipated (for example, that modularity, composability and interoperability may lower the price of production), and some of which cannot.
   - The sewing machine, for example, 'evolved from significant technical innovation by many workers, producing stitches that could not be made by hand. Alongside innovation in business practices such as the Patent Combination, Hire Purchase and Part Exchange, the sewing machine industry inaugurated major advances in "interchangeable manufacture". To produce the millions of cheap machines, each containing many small precision parts, required its own machine tool revolution' [444].

6. Technology change and innovation is a confrontation with uncertainty.
   a. Technology change is constrained by the path dependence and interdependence of products and processes, as well as inevitable but unpredictable factors unrelated to the nature of those products.
   b. As a result, innovation is not always a conventionally manageable process, which proceeds according to a set of logical steps, and in which risks can be fully assessed through mechanisms of analysis and rationalisation.

However, there are rational processes for proceeding in the face of this uncertainty, including continual measurement, building in flexibility and adaptability, and evaluation (Chapters 3, Section 7.6)

Implication/relevance for government for facts 1–6

The impacts of any technology are differential and context dependent. When seeking to understand the potential impacts of a technology, the context in which the technology is being deployed should be considered (e.g. can the population of people for which the technology is designed and deployed actually use it?).

Analyse the potential impacts of any new technology at a fine-grained level, not just in aggregate across the population, because aggregates can hide the differential impacts.

Australia's social welfare safety net can help to:

1. Mitigate the negative impact on workers whose industries disappear or whose skills become obsolete
2. Redistribute resources more equitably
3. Improve access to and understanding of opportunities offered by new technology
4. Make the benefits of new technologies accessible to all through programs that promote technology literacy for all Australians.

Despite, or perhaps because of the problem of uncertainty, there is value under some circumstances in behaving as though innovation proceeds rationally and predictably, as to do so allows planning.

The above stylised facts 1-6 point to the limits of techno-solutionism, given the complexities and inherent uncertainties at play when trying to anticipate technological change and consequently, the impacts of technology in a specific context.

4.3.2 Globalisation

ICT and transport technologies, in particular, facilitate globalisation. Globalisation critically affects Australia's socio-cultural setting, its economy, governance, and security.

7. Technology improves and increases the flow of ideas, values, communications, people and capital [555].
   a) Power may shift from national governments to multinational corporations, with consequences for Australia's system of governance and democratic principles.
   b) More generally, technology facilitates the shift of power at all levels with differential consequences.
   c) The ease of travel and requirement to travel may contribute to the perceived failure of 'traditional' family structures – children move away from their parents for study and work, meet partners from overseas – this means fewer grandparents available for child care, and fewer children available for care of elders. Globalisation may directly effect and affect social and economic change.

8. Technologies which facilitate aspects of globalisation may make Australians more tolerant and cosmopolitan.
   a) Australians are more aware of the actions and values of people in other countries than they were even a few decades ago.
   b) Australians may be more aware of how other countries see Australia and its government.

9. For some people and industries struggling to adapt, globalisation has encouraged a fear of change – perhaps even more than technology directly [555].
   a) Some express a fear that globalisation and immigration have or will overwhelm national cultures and Australian identity, which may be subsumed by a global civil society. These people are confused about the role of supra-national government relative to national government, expressed in suspicion of international treaties, international obligations, multinational corporations, and the United Nations.
   b) These impacts on culture and governance, real and perceived, may be exacerbated by further likely improvements in ICT and transport technologies.

Implication/relevance for government for facts 7–9

Globalisation and technology have differentially affected Australians, producing costs and benefits to the nation, as well as those who have benefited and others who have been disadvantaged, both domestically and internationally [555].

4.3.3 Australia's social and cultural systems

10. Technology and human nature are intimately related: just as we change technology, using technology changes us (see Box 10). It changes the way we act, think, learn, and socialise, and change in practice effects physical changes which can change the expression of genes:
   a) Examples of physical and selective/adaptive changes:
      - Epigenetic effects (generational effects of nutrition or smoking)
      - Technological innovation which affects fitness – tools for butchering and use of fire for cooking are linked to changes in the human gut and jaw; wearing

clothing is linked to decrease in body hair – both of these technologically-mediated behaviours allow the diversion of more nutrients to the brain
    - Physical change to individuals – for example, the rise of the modern office linked to increased sedentariness and later metabolic disease (may also have epigenetic effects).

b) Examples of cognitive changes:
    - The development of alphanumeric systems and the invention of literacy and numeracy has had profound consequences for memory and oral transmission. These implications are currently being played out in indigenous communities in Australia in the race to preserve indigenous languages.
    - Comparable cognitive changes to those accompanying the rise of literacy are rehearsed in the rise of moveable type and the Gutenberg press in the 15th century; the widespread use of typewriters during the 19th–20th century and late 20th century word processors; the rise of computers with word-processing software; and the rise of the world wide web [777].
    - The changes in communication practice are accompanied by widespread anxieties. For example, some research suggests that people who read on-screen come to think differently from their book-reading predecessors; likewise typing versus handwriting may introduce fundamentally new cognitive processes. Both these notions are controversial however.

c) Niche construction theory suggests that organisms can alter the selective pressures acting on them by modifying their environments, which in turn modify the selective pressures on those organisms [342]. For example, Neolithic *Homo sapiens* cultivated plants and animals which encouraged long-term settlement, which in turn led to increased population density and nutrition-related physical changes. Any major technological changes may alter evolutionary pressure on human beings.

d) A central theme of transhumanist philosophy concerns the use of technology to engender a new 'posthuman' species [1050]:
    - Transhumanism revises popular understanding of what it is to be disordered or unhealthy. With the rise of tools to enhance hearing and vision, for example, or new tools to promote strength and fitness, what was previously considered normal may become viewed as disordered.
    - The point above has implications for the potential social impacts of enhancement including gene therapy and cybernetics, for increasing or entrenching inequality.
    - 'Extended mind' tools include the internet, smartphones, wireless platforms. Earlier extended mind technologies include diaries, spreadsheets, calculators, computers, cameras, other tools for memory and thought.
    - However given that the uses of technology continually change what it is to be human, this suggests that being human is a process rather than an endpoint. In this sense 21st century humans will be no more 'posthuman' than were their ancestors relative to their predecessors.

e) The rise of electronic social media has been linked to changes in the way people interact with each other leading to a decline in social capital, although this is contentious. It does seem that electronic social media, like any widespread shift in the ways people communicate and interact, has been accompanied by a significant shift in the ways and the places that people perform social relationships. *Homo sapiens* is a social species, so any widespread and fundamental change to the way people socialise implies a change in the way people are human.

Implication/relevance for government for fact 10

The adoption of a new technology, particularly technologies such as ICT or electrification, which pervade many different aspects of human societies, has the potential over time to change what it means to be human.

11. Because of the entanglement of humanity and technology, a fundamental impact of technology and technology change is *change in social systems* – including cultural, democratic, security, and economic changes.

12. Change in intergenerational relationships:

a) The impact of the information economy and widespread availability of electronic search engines on intergenerational relationships can be to undermine experience as a source of knowledge, thereby changing the dynamic between generations as elders lose authority and value as information resources. This process may mirror earlier shifts in technologies of literacy and numeracy.

13. Technology has contributed to conditions favouring population growth and demographic shifts.

a) Reliable food, improving nutrition, and medical and public health innovations allowed populations to increase by decreasing mortality (in particular, child and youth mortality) and by increasing life expectancy (people live longer).

b) Technologies for transport have facilitated population shifts via migration.

Implication/relevance for government for facts 11–13

Large and rapid shifts in population can cause overcrowding in urban areas, rural and regional decline; impact on provision of services; impact on social cohesion; overpopulation in areas where people lack access to family planning. These factors may exacerbate existing inequality and poor access to technology.

14. The unequal distribution of resources can be compounded by new developments in technology and new products (although under some circumstances it can have the opposite effect).

- Regional differences play a role in maintaining and exacerbating uneven access to technology, including ICT. For example, access to and the speed of broadband technology is greater in urban areas than rural and regional areas of Australia. This can perpetuate problems of isolation and uneven opportunity, as well as uptake and adoption.

15. The forms technology takes, arises from their interplay with economic, social and cultural systems, and can contribute to changing these systems. Technology may have facilitated the emergence of a more heterogeneous Australian national culture:

a) The rise of individualism and reduced acceptance of political authority:

- The key change has been towards a society that is more individualistic and is less accepting of the authority of politicians and public servants than in the 1960s and 1970s, and even more so compared to Australian society before World War II. This change was prompted or at least assisted by a number of technology innovations, most notably television.
- The pill has aided the independence of women, and liberated sexual behaviour and arguably morality/values.
- Some commentators have claimed that work patterns, television, the VCR, dishwashers, microwave ovens, computer games, multi-car households, the internet and wireless platforms, and increasing secularism are reducing the scope for family activities and engaging casually with extended family and neighbours leading to a change in social capital [555] [1016]
    - Since the rise of widespread electronic communication and networked social media, concern has grown that 'traditional' social networks are breaking down [862,1016,1062]. Some have blamed this breakdown on

the rise of social media and other internet-based communication (e.g.[1062]), but there is other evidence that suggests that ICT, like other disruptive, pervasive technologies, simply shifts the generation of social capital to different forums.

    - As people email more, letter-writing may decline.
    - As people text and instant message more on their smart devices, voice calls may decline, as may email.
    - As the physical distance between people is mitigated by increased electronic connection, people may be less inclined to join culturally-based social clubs in the material world, and instead participate in online forums.

  - Research over the last 15 years suggests that 'there is either no relationship or a positive cumulative relationship between internet use, the intensity of sociability, civic engagement, and the intensity of family and friendship relationships, in all cultures—with the exception of a couple of early studies of the internet in the 1990s, corrected by their authors later' [167]. Changes in social cohesion were apparent before the rise of widespread networked ICT communication [4]
  - The rise of two-income households has led to greater material affluence accompanied by time poverty. Together with longer lifespans, greater mobility, and fewer children to care for the elderly in old age, this time poverty may have led to a shift from earlier 20th century models of multi-generational households toward a situation where the care of elders (and young children) is outsourced.

b) The rise of pluralism and tolerance, as expressed most obviously by multiculturalism, and a rise in humanism.
   - Globalisation has been critical in helping to bring this about.
   - The ICT revolution of the last 20 years has led to new expressions of collective action in the form of online activism.
   - Radio, television and the internet have increased access to information about government, and how others (including those in other countries) regard Australian governments, social systems, and politicians.
   - The rise of electronic social networking may help to spread ideas, leading, for example, to lower face-to-face church attendance, or to new models for college education which eschew formal campus attendance.
   - Alternatively, the tendency of people to associate and bond with similar others may see people remain as entrenched in old patterns of belief and behaviour within electronic networks as they may be in their physical neighbourhoods.

c) Globalised 'networked sociability':
   - A new kind of sociability, 'networked sociability' [166,168] arising from the ICT-derived culture of autonomy and individualism, has emerged over the last 20 years, together with changing socio-political practice, and the rise of networked social movements and networked democracy. Castells traces 'a dramatic increase in sociability, but a different kind of sociability, facilitated and dynamized by permanent connectivity and social networking on the web' wherein 'the virtual life is more social than the physical life'. This is networked sociability. He observes that 'the ongoing transformation of communication technology in the digital age extends the reach of communication media to all domains of social life in a network that is at the same time global and local, generic and customized, in an ever-changing pattern'.

Implication/relevance for government for facts 14–15:

The use of technologies play a role in shaping national culture. Australian national culture now appears more heterogeneous than 50 years ago. Note also that some traditional Australian values have largely remained unchanged, such as the rhetoric of the fair go (enshrined in legislation) [556].

> The persistence of this trope – the 'fair go' – may contribute to anxiety within certain sectors in Australia that Australians are inclined to look to government assistance, at least in adversity. There is considerable public support for the institutions (like Medicare, the aged pension, Newstart, Australia's public education systems, the minimum wage, and the new National Disability Insurance Scheme), that comprise Australia's social welfare safety net, as well as opposition to governments withdrawing tariffs and subsidies for Australian industries. However, broad support for government assistance to Australian small and medium enterprises, rural, regional and manufacturing industries, and the social welfare safety net is not indicative of a characteristic specific to Australia. Nor does it suggest that Australians are overly reliant on government support compared to other western countries. There is no clear comparative evidence that Australians are less entrepreneurial and risk taking than citizens of equivalent OECD countries.

4.3.4 Governance and democracy in Australia

16. Technology has had a profound impact on democracy in Australia and its system of governance.

a) For example, television changed the nature of politics and cabinet government, page 17 of [555]:
   - The decline of the hustings and the town hall meetings, following the introduction of television, has led to a change in the nature of political communication, with a much greater focus on the 'leader', reducing the electoral role of politicians other than the leader and disenfranchising ordinary party members. This along with the consequent development of the 24 hour news cycle, has changed participatory democracy and Australia's system of cabinet government in favour of a more presidential system.
   - Since the arrival of television as the main means of communicating with the electorate, the cost of advertising for political parties has grown enormously. This in turn means that parties are more dependent on large donations and other forms of fund raising than in the past.
   - On the other hand, the rise of the electronic social media, as demonstrated during the 2012 US Presidential election, allows parties, politicians and activists to communicate cheaply with lots of people and even raise money from them, potentially freeing up a means for smaller parties, independent politicians, and activist collectives to reach wider audiences. However, data analytics are not cheap, and the sort of targeted social media campaign used by Obama's supporters is not likely to be available to grass-roots activists or independent politicians.

b) More recently the internet has changed the nature of citizen interaction with government and fellow citizens, allowing greater devolution:
   - This type of devolved political interaction may lend itself to a concentration on single issues rather than expression through the more comprehensive agendas of the traditional political parties.
   - Citizen advocacy in the form of online petitions may cause elected officials to give excessive attention to issues that receive a lot of 'up votes', instead of taking a more inclusive and strategic approach to governance and policymaking.

c) There may be ramifications for democracy more broadly of these changes in the mode of communication, for example, the implications for the justice system of shows like:
   - The popular non-fiction US *Serial* podcast, which explores a possible wrongful conviction in a 1999 Baltimore murder case. *Serial* has been accompanied by extensive investigations by its large body of somewhat obsessive internet-savvy fans, leading to criticisms that the podcast may prejudice re-examination of the

case, as well as inadvertently leading devotees to invade the privacy of the people involved.
- The first season of the true-crime drama miniseries *Underbelly*, first aired in 2008. Its airing was postponed in Victoria because of an ongoing court case for which its fictionalised storyline might have been prejudicial – but was shared on social media in the state, despite the court order banning it.
- Following the Boston Marathon bombing in April 2013 amateur investigators speculating on Reddit and Twitter misidentified suspects and published the wrong names widely on social networks; these names were subsequently picked up by news blogs and websites within the space of hours: 'thousand upon thousands of tweets poured out, many celebrating new media's victory in trouncing old media'[641]. Democracies use technology to gather information for governance [665]. Mass information processing has made policy development more analytical and service provision can now be less uniform and more responsive to individual demands [555].

17. Technology has changed the organisation of work and workplace cultures[555]:

a) The use of technology to improve business analytics in particular has led to a dramatic increase in the proportion of workers whose main capital is knowledge e.g. managers or professionals. The productivity of knowledge workers depends on continual learning and innovation, self-management, and quality of output, as well as quantity of work. This in turn has led to a change in management-employee relations as employers negotiate different management styles to get the best out of knowledge workers [311,434].

b) Also has implications for traditional forms of collective action (i.e. unionism).

Implication/relevance for government for facts 16-17

Many observe a diminution of trust in government in advanced democracies, making government more difficult and has prompted some changes in Australia's system of governance. Much of this loss of trust reflects social, cultural and economic changes, which in turn have been influenced by new technologies.

4.3.5 The economy

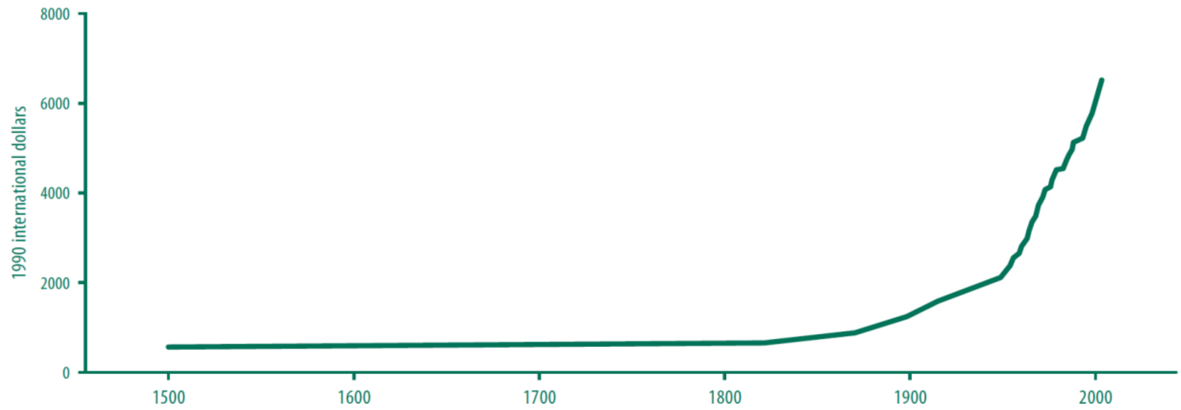


Figure 11 Australian GDP/capita 2010 dollars (data sourced from [515]).

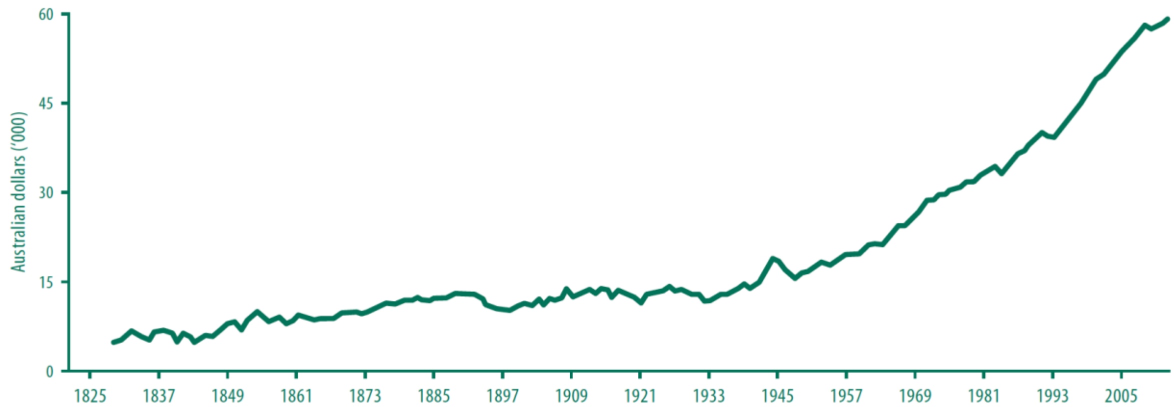


Figure 10 World GDP (1990 international dollars) (Source [1128])

18. Changes to technology are the major source of long term growth in GDP/capita for developed countries like Australia [597]; confer Figure 11 and Figure 10. Technology determines the productivity frontier for developed countries and as technology advances this 'frontier' is pushed out allowing productivity to grow. Developing countries are 'inside' the frontier and during their early development they can 'catch-up' to the frontier already established by the most developed countries, thus allowing the developing countries to grow faster during this catch-up phase.

Total GDP growth is also a function of technology and not just GDP/capita because technology has supported population growth by way of improved food security, nutrition, health, and transport.

Implication/relevance for government for fact 18

Technology and economic policy are inextricably linked. When evaluating new technology, government needs to explicitly consider the benefits as well as the risks of that technology. It is often easy for government to simply note the risks or bow down to vested interests who favour existing technology. However, blocking or delaying new technology due to overweighting the risks relative to the benefits (e.g. GM crops, most medical drugs) can slow economic growth and cause major loss both in terms of standards of living and (literally) loss of life (e.g. Australia insists on replicating FDA processes for drug approval, and the introduction of 'golden rice' being delayed by governments in developing countries to the detriment of undernourished citizens).

19. Changes to technology, while often occurring at an industry or company level, lead to gains from trade that benefit all countries that directly or indirectly use or otherwise adopt the technology. In other words, technology is a 'positive sum game'.

Implication/relevance for government for fact 19

Most technology change is gradual and so not all that disruptive. Instead there is typically time to adapt and adjust. This time can be utilised by developing a good social safety net along with programs for multi-skilling and re-skilling.

There should be an open policy to technology adoption and trade involving new technologies. While there should be appropriate legal rules of intellectual property, these rules should not be used to protect an existing technology or prevent the development/adoption of new technologies.

20. Technological development and adoption is not a linear process. In particular, the adoption of a particular technology is usually history dependent and may be subject to a variety of factors relating to relevant markets (e.g. bandwagon effects [896]).

Implication/relevance for government for fact 20

Governments need to be aware that their own action (or inaction) may itself affect the adoption process. In particular, government regulation may inadvertently be biased towards particular technologies or may create artificial barriers to the adoption of new technologies.

21. The gains from technological change may be unevenly distributed in the short and medium term. In particular, technology may make certain skills obsolete and can lead to income transfers between groups.

a) However there is no historic evidence that technological change leads to long term increases in unemployment (despite significant growth in labour supply in most developed countries in the last century) (Appendix C.7, [868]; see also footnote 4 in section 1.4).

b) It cannot be assumed that technological change will always have a neutral impact on income distribution but neither is it clear in which direction it will impact. Although if technology is a reaction to shortages then the price of whatever is in short supply can be expected to decline relatively: there have been epochs in history when technological change favoured large scale production (e.g. Henry Ford and the motor car) which led to de-skilling of the labour force, and increased demand for semi-skilled workers whose wages probably rose relatively. By contrast, more recently, there is evidence that the growth in jobs has been concentrated in highly skilled occupations which suggests that technological change has favoured these jobs and their relative wages, especially in the USA.

Implication/relevance for government for fact 21

Short term policies to deal with inequality in the workplace caused by technological change should not seek to delay or impede the adoption of new technology, but should focus on facilitating worker transfers and re-skilling to enable those harmed by new technology to be protected and to adapt to the change. It highlights the importance of Australia's social safety net.

22. Government regulation may have the effect of encouraging particular technologies or may act as a barrier to adoption of particular technologies.

23. New technology raises new regulatory issues for governments. Regulation serves a variety of purposes.

Implication/relevance for government for facts 22–23

When considering Australia's economic growth, the government needs to make sure that it is not implementing policies that artificially impede the ability to adopt and adapt to new technology (e.g. by adopting laws that are technology specific, by having slow processes to change laws and processes for new technology, by having rules that are biased towards incumbents and slow entry of new technology). Good governance means having rules and writing laws that focus on outcomes not specific technologies so that new technologies can be easily adopted if they are preferred.

Technologies emerge into existing regulatory environments. Often existing regulatory systems may be sufficient to deal with the impacts of new or emerging technologies, especially if regulations are written to regulate the use, not the thing. New technology does not imply 'less regulation'. It implies 'different regulation' [723].

Policy makers and legislators should attempt to craft 'technologically neutral' regulations where appropriate. They should be aware of changes to technology and how these changes potentially make existing technology, and existing regulation, redundant.

24. Vested interests will have strong incentives to place barriers (including government regulatory barriers) in the way of adoption of new technology if such adoption makes the vested interests worse off.

Implication/relevance for government for fact 24

Government should be wary of the pressure imposed by such interests relating to technology and ensure that policy is in the broad public interest rather than favouring particular interest groups.

Governments should be very wary of claims that 'national champions' are needed to support technological innovation and adoption. There is no economic evidence to support such claims; see Section 7.9.3.

25. New technology creates new opportunities both for competition and to limit competition.

a) For example, technological change may lead to increased industry concentration (logistics and supermarkets is an obvious example).
b) The creation of market power through new technology may or may not create broader economic issues depending on whether or not the market power is transitory and whether or not it is abused by the relevant businesses (which is not always obvious[41]).
c) Economies of scale and scope may be one underlying reason why technological change increases market concentration and/or increases market power.

Implication/relevance for government for fact 25

There is no economic consensus on the relationship between market structure and innovation. In other words, there is no reason as a matter of economics why there should be a positive or negative relationship between innovation and competition.

Australia needs robust competition policy and antitrust laws that recognise the interaction between technology and competition. In particular, the law should recognise that competition policy is about protecting competition (as a process) rather than about protecting individual competitors. Antitrust laws need to recognise the dynamic role of markets where there is technological change and the potential competition to incumbent firms provided by near-term technological changes.

---

[41] Confer the current debate about Amazon and Hachette [413].

4.3.6 Australia's security system

26. Almost any technology has security implications of some kind.

a) All technology can be used to both strengthen and weaken security. Technologies which provide considerable advantage in the form of energy security (for example, the use of fire, electrification, fossil fuel technologies) are not always controllable, and when uncontrolled can threaten human security:
   - Early tools such asa stone axe, a spear, or bow and arrow, were highly beneficial to the safety and comfort of humans while at the same time they served as instruments for injuring people and destroying property.
   - Fire helped to shape humanity physically, via the ability to cook food. A hearth provided warmth and protection from predators, encouraging new forms of sociability. It has been used to shape landscapes. But when out of control it destroys lives and property.
   - Electricity infrastructure transformed economies around the world, but if poorly maintained, can start fires, electrocute the unwary or naïve, and fail at critical times; it is powered by energy sources which come with their own negative externalities.
   - While coal-burning helped fuel an Industrial Revolution, coal mining was a scourge of the working classes well into the 20th century, due to both catastrophic mine accidents, the negative medium- to long-term health effects for miners, and the sometimes catastrophic effects of domestic coal burning. Coal mines and coal-fired power stations continue to harm people, directly and indirectly, due to accidents, pollution, and the contribution of coal-burning to climate change, but coal and other fossil fuels also provide material wealth and security to millions of people.

Implication/relevance for government for fact 26

Differential impacts may fuel concerns about risk, but they are a factor in all technology choices and cannot be avoided. Refusing to make a choice or delaying decisions come with risks of their own.

27. The emergence of any radically new technology creates uncertainty and eventually results in changes to the existing order, with consequent winners and losers.

a) Technologies, their producers and their consumers are in an arms race fuelled by competition and market forces, costly signalling, threat and fear, but also spurred by philanthropic feeling. For example, researchers in 2005 who recreated the 1918 influenza virus, were prompted by the impulse to prevent or control potential flu pandemics. But critics suggested that publishing the analysis raised the risk of future accidental pandemic or bioterrorism [1101].

b) Human understanding of risk is generally very poor, often fuelling fear and anxiety associated with the introduction of new technologies. Anxiety and feelings of existential risk are not unusual, and have been associated with technologies that are now taken for granted (for example, as described by Plato in his dialogue *Phaedrus,* relating to the rise of literacy and associated decline in memory; and the early 19th century Luddites were concerned about threats to their livelihood engendered by technical innovations, protesting against and destroying labour-replacing machinery). Modern anxieties and existential concerns may be associated with biotechnology (including genetically modified crops), widespread vaccination regimes, the use of nanotechnology, the growth of increasingly capable and pervasive networked monitoring systems, and anticipated advances in artificial intelligence, among others.

Implication/relevance for government for fact 27

Because technologies emerge into existing regulatory environments, and because legislation can take time to draft and implement, regulation may be insufficient at times to deal with the impacts of technology. Existential and security concerns may result in overreaction from regulators and a risk-averse public, for example in the case of biotechnology interventions such asgenetically modified food (represented as 'Frankenfood') or fully autonomous vehicles. On the other hand, when projected impacts are sufficiently far in the future, legislators may want to avoid the negative associations of intervention and refuse to introduce (or revoke) useful regulation.

Perceptions of risk can have perverse consequences: More people died after 9/11 due to the *additional* traffic accidents caused by people being afraid to fly than in the 9/11 attacks [416,417,717]. But such harm is dwarfed by the potential risks due to cyber-attacks, which in turn are dwarfed by those of unmitigated climate change[42].

Policy makers need to be aware that technology creation and adoption is dynamic. Any attempts to safeguard security by intervening on these 'arms races' (attempting to influence behaviour or favouring certain options) may have perverse outcomes.

28. The security of major infrastructure and systems, including energy, water, transport, health, biosecurity, environment, food and communication, is of significant concern to nation states and corporations.

a) The pervasiveness and interoperability of electronic information and communication technologies has heightened security and privacy concerns associated with networked systems.
b) In an increasingly networked and interoperable world, private, public, and civil institutions become more dependent on information systems and more vulnerable to attack by cybercriminals, hackers, online activists, nation-states, and even their own employees.
c) These threats may be inadvertent or malicious, and may originate from anywhere. They may be acts of social disobedience, of personal malice, they may be seeking criminal advantage, or they may be acts of warfare.
d) As a result of these interconnected systems, cybersecurity will remain a major issue. For example, information systems are now vitally important to government, industry and society but there is an increasing risk of information security breaches amplified by the interconnectivity of the networked structure of information technology. A safe, secure and trusted e-commerce process is essential to economic growth as on-line commerce continues to grow rapidly in Australia and globally.

---

[42] Barack Obama was quoted as saying that climate-change is a greater threat than terrorism [551]. One can crudely *underestimate* the deaths due to the use of coal as an energy source alone (this of course is not deaths due to climate-change, but it serves the point as it is certainly an underestimate of the costs of coal as an energy source). There are approximately 30,000 deaths *per year* in the US alone due to coal pollution alone [1112]; there are 180,000 deaths per year worldwide due to soft drink consumption [22] and 480,000 deaths per year in the US and 6 million deaths per year worldwide due to tobacco smoke [[170], [1147]. The average number of deaths per year due to terrorism *worldwide* varies according to source: from around 500 per year (with a peak of 4500 in 2001) [537] to a figure of 13,288 people killed *worldwide* in 2011 due to terrorist activity [1082]. Even allowing for the uncertainty in these figures, the comparison is clear. (In fact, within the US more people die by being crushed by their furniture or televisions than they do as a result of terrorism [1114,1156]!) It is reasonable to extrapolate the US numbers to Australia, in which case it is clear that coal is (currently) more dangerous than terrorism. The point of this comparison is not to trivialize *any* of these concerns; it is simply to illustrate the value of looking at the numbers in a *relative* fashion. In terms of the biggest security threats, the US Director of National Security stated that cyberattacks are the number one current US security threat [90].

However, crime follows opportunity and on-line risks pose a serious threat to individuals, businesses, industry and governments [202,277,1072]. Criminals have adapted methods of identity theft, financial crime and other crime for use on the internet and these crimes have an impact on the costs of business[43]. Tracing offenders, however, has proven extremely difficult given the rise of anonymising technologies[44], bulletproof internet service hosting and lax jurisdictions in the cyber environment.

Implication/relevance for government for fact 28

As a result, Australian institutions will have to make increasingly thoughtful trade-offs between the value inherent in a hyper-connected world and the risk of operational disruption, intellectual property loss, public embarrassment, physical harm, and fraud that cyber-attacks create.

29. As observed elsewhere in this report, technology choices always involve a trade-off and an opportunity cost. There has been a trade-off between privacy/obscurity, sociability, and security at least since the rise of the nation-state. This arms race, which continues today, is facilitated by technical innovation and shifts in control and availability of technologies for information and communication.

a) A current example is the rise of platforms for anonymous internet browsing in the face of increasing state requirements for the retention of personal electronic data.

b) Social media platforms have monetised personal data, but their business models also rely on their ability to protect this data from external attackers, including state security agencies as well as non-state actors.

c) Opportunism from the state may fuel citizen anxiety about privacy, obscurity and the actions of security agencies. For example, Centrelink now accesses more personal information than any other state enforcement agency, routinely investigating welfare fraud using powers the Australian government originally sought to target terrorism: 'It's a simple procedure: a Centrelink agent fills in a form, gets approval from elsewhere in their department, and is authorised to tap into personal phone records and email history. The subject is not informed' [208].

d) Unlike 'low volume/high value' cybercrime that targets banks and financial services, or government or military targets and requires advanced hacking capability, many more victims fall to spam and simple on-line deceptions that enable malware to reach 'high volume/low value' targets that are less likely to have effective anti-virus or other countermeasures in place. In 2013 spam alone was estimated to account for about 80-90% of the total global email traffic. Circumvention of defences is common, and new techniques in spam delivery outpace methods designed to filter it.

---

[43] For example, the internet-related market in the United Kingdom is estimated to be worth £82bn a year and British businesses earning £1 in every £5 from the Internet. UK research shows that that 81% of large corporations and 60% of small businesses reported a cyber breach, with each breach estimated to cost £600,000 - £1.15m for large businesses and £65,000-£115,000 for small companies [789].

[44] An increasing number of tools and techniques such as Onion Router (Tor) and Virtual Private Networks (VPN), allow a user to browse the Internet from a device located in another country, often a 'safe haven'. The literature also notes the role of organised crime in thriving underground on-line markets for stolen data and other illicit products. Victims are also increasingly targeted via the use of data acquired about their habits and interests [141].

Implication/relevance for government for fact 29

There is an apparent contradiction between popular discourses about freedom and privacy with a desire to protect/be protected from violence, exploitation and crime. Governments and businesses need to balance trust, accountability and transparency with secrecy and security concerns.

4.4 Anticipating and reacting to impacts

It is clear from the foregoing material that the impacts of technology are numerous, various, complicated, often interrelated, and difficult to attribute with implications for Australian society, cultures, economy, governance and security systems. There is strong public interest in the impacts of technology, and strong social, economic and political incentives for firms, industries, organisations and government to anticipate, or better yet to predict them. Indeed, this report and projects like it are motivated by these same imperatives: project question Q3 seeks advice on 'the potential impacts of new and emerging technologies' on Australia; project question Q4 asks what are and what will be the key drivers of the uptake of new technologies by industries and firms, and the role of government policy; and project question Q2 asks to what extent future impacts can be predicted.

Imperfect information about the past and present and uncertainty about the future complicate the answers to all these questions. Lack of data, overdetermination, interdependence of technology and its impacts, and poor data interoperability all contribute to uncertainty.

The value of a technology is measured partly in its assumed impacts on social, cultural, democratic, security and economic systems. Under specific circumstances, it may be possible to associate technology X with impact Y. However, the difficulty of identifying a causal relationship between an intervention and an observed change in the target system (overdetermination) is a fundamental problem for technology evaluation, business planning, regulation and public policy [223]. Sometimes these effects only become clear long after the introduction of a technology [907] – for example, the contribution of vehicle emissions to the greenhouse effect or the transformative effects of ICT seven decades after the first electronic digital computers. This time lag is due to several factors, chief among them the interdependence of technologies, the incremental nature of small impacts, and the gradual nature of change (Chapter 2), which in combination create difficulties in attributing particular impacts to particular technologies in retrospect.

Evaluation can be retrospective, ongoing, and prospective. Evaluation can improve analysis of the impacts of technologies and thus may lead to better uses of technology, see Chapter 6.

5 Meanings, attitudes and behaviour

Summary

Meaning, attitudes and cultural influences all play significant roles in how and why technology is created, implemented and adopted.

Technology cannot be considered in isolation from individual and collective values, beliefs, attitudes, cultures and imaginaries; many emerging technologies trigger debate about ethical, legal and social implications from invention to use.

Attitudes to technology are complex and change over time and do not necessarily align with behaviour. It is difficult to predict the attitude a person will have to any given technology, and whether or not a technology will be adopted.

People often attribute a kind of agency to technology, imbuing technology with human characteristics. Attributing positive agency to technology can increase its adoption.

Trust is significant for all aspects of technology. The issue of trust becomes important because of the meanings associated with technology and the uncertainty surrounding technology change.

When information is limited, complex or contradictory, people tend to make judgements driven by values and beliefs rather than the information provided.

Social norms and practices influence the choices people make to adopt and use technology.

The way in which people experience technology is as much about what people think and feel, as it is about what people do [803,805]. The meanings and attitudes attributed to technology shape how people imagine technology, create technology, choose to adopt technology (or not) and use technology [650,804]. They influence the political, economic, social, and cultural implications of technology, how technology is predicted, assessed and governed, the nature of a country's innovation system and culture, and how people put technology to use. People's interaction with technology is influenced by values, beliefs, identity, emotions, experience, social norms, social structures, cognition, context, location and culture. These phenomena interconnect; they motivate and shape one another as technology and social contexts both change.

This chapter examines how meaning, values and beliefs inform the meaning of technology for the individual, the workplace, a collective group or nation. It explores the different aspects of attitude that inform the choice to engage with technology or not. People make decisions about technology based on its meaning, their past experiences and how they perceive the technology will affect their everyday life. These factors influence decisions made by creators, engineers, scientists, users, businesses, activists, politicians and policy makers. Meaning, attitudes and cultural influences all play significant roles in how and why technology is created, implemented and adopted.

5.1 Meaning, values, and identity

Science and technology cannot be considered in isolation from values; many emerging technologies trigger debate about ethical, legal and social implications from invention to use. Values can spark debates about the regulation of genetically modified food, anxiety about the future implications for humanity of increasingly intelligent machines, or concern about domestic use of drone technology. The value systems of all the people involved in technology development – users, marketers, inventors, regulators, investors, scientists, engineers – will influence decisions about that technology. These factors are as important as economic factors in the adoption of technology; economists now recognise the importance of meaning for understanding economic behaviour [552].

Technology is not just something that people use or admire, it is embedded in their lives. Most people are not employed as inventors or engineers and do not understand technology in a technical sense but people experience it through its influence on their daily lives, by the way it has shaped their world, by what it allows them to do and how those practices make them feel. For instance, mobile phones, e-mail and social media support relationships and activities that enrich lives, but do not require technical expertise to operate. These technologies provide people with alternative ways of doing what they already love to do: communicate, and create and maintain relationships. Similarly, to many people a car is not just a machine used to travel. Marketing campaigns linking positive human emotions and values such as freedom, control and status to the car have greatly influenced public perception and promoted its widespread adoption (Appendix C.5, [765]). When people buy products, they often buy meanings – for example, a luxury brand, offers status, and items of fashion help people to define themselves within or against a collective identity, or to express a particular image and this motivation has long been used in marketing and advertising.

Technology is sometimes associated with strong meanings about human emotions, values, beliefs, and aspirations. It is often viewed as a sign of progress, modernity, productivity, freedom, and affluence (Box 13). For example, technologies used for exploration beyond Earth were accompanied (especially in the case of rocket launches) with much ritual, national ceremony and myth-making. Regional identities are also caught up with technology: South Australia celebrates the 3200 kilometre long Overland Telegraph completed in 1872 as one of the greatest achievements of the 19th century [1044]. Similarly the town of Beaconsfield, Tasmania, erected a fluoride memorial to celebrate its status as the first town in Australia to fluoridate its drinking water in 1953 [714].

Technology can evoke excitement, wonder and awe. Historian David Nye has dubbed this effect the 'technological sublime', borrowing from ideas about the sublime (or awe-inspiring) in nature. Engineered structures associated with the technological sublime include railroads, bridges, ships, and buildings, for example, the megastructures of Isambard Kingdom Brunel [344]. The electric light was met with similar enthusiasm and likened to a spectacular natural phenomenon and religious miracle [775]. Enthusiasm for a technology or technology artefact can help forge regional or national identity, creating a social unity and shared emotions. For example, when the Sydney Opera House was assessed for its true value to Australian residents and international visitors in 2013, its iconic and experiential values were recognised. The cultural heritage, brand and identity associated with its innovative architectural style and structure is estimated to bring $2.1 billion in present value to the nation over 40 years [265], indicating there are different ways that society can value technology.

Box 13: Recognising value in the meaning of technology

Based on their values and beliefs, people adopt attitudes that confirm and reinforce how they think their society should work. Values are an especially powerful set of meanings that groups are deeply invested in and influence the actions people take. In his book *Meaning in Technology*, Arnold Pacey describes how farmers with different value systems have different attitudes to the way they farm their land. Illinois farmers of German descent regard ownership of land as a sacred trust. Hence their philosophy and farming strategy aims to maximise long-term security by taking care of the land for future generations. On the other hand, North American farmers of English descent are more commercially oriented and regard land as a commodity and agriculture as a business. There is greater concern by this group to maximise financial return than to preserve the land for future generations [805]. As Pacey's example illustrates, practices are shaped by value systems. This applies broadly to people's uses of technology, and is part of making a technology or suite of technologies at home in the world.

Adoption, resistance, use, and collective and individual experiences of technology are informed by attitudes, beliefs and values. Attitudes draw on individual belief systems and the moral and political domains within which a person operates, both individually and within groups. There is no simple relationship between attitudes and technology. This complexity and contradiction are often highly visible when activist, lobby, advocacy, business, or industry groups seek to resist or influence technology introduction or implementation. Public attitudes to emerging technologies are also associated with trust in scientific institutions, available information, and perceived risks and benefits [495].

This section considers the roles of values, culture, identity and imaginaries from a range of different perspectives.

5.1.1 Values and beliefs

Values relate to a person's principles and their judgement of what is important in life, and beliefs are firmly held opinions one accepts as true and real. A person's perception of risk will reflect and reinforce their worldview. A person's attitudes and perceptions of risk is shaped by their values and beliefs. For example, people opposed to genetically modified food have been found to dismiss scientific evidence because they are more concerned about the manipulation of nature and market power of corporations than about specific improvements resulting from genetic modification. In the case of genetically modified Golden Rice – developed by a public institute to help address Vitamin A deficiency in poor countries – debate about the scientific evidence will often focus on the belief that scientists cannot remain commercially impartial, given the influence of big business. The attitude toward genetically modified crops may be linked to mistrust of large corporations (Appendix C.4,[932]).

Worldview is one way used to describe how a person interprets the world they live in and what is most important to them. The impact of personal worldview on risk perception and decision making is suggested to be relatively small if citizens are exposed to people of diverse worldviews i.e. similar and opposite to their own, on both sides of the debate. This way participants on 'both sides of the debate can honestly and credibly claim that their goal is not to manipulate the public to accept one position; rather it is to enable members of the public to decide for themselves what position to adopt' [544].

5.1.2 Business and workplace culture, identity and professional norms

In sociological terms, an organisation consists of the set of shared beliefs about its structure, processes and culture. Business identity is a shared understanding by workers about the central and distinctive aspects of the organisation which informs procedures, recruitment, strategic decision-making and action (or inaction). The external identity of a business is also important to the way in which the organisation is understood by its customers, suppliers and other stakeholders. The continuity of identity in a business or industry provides stability. Organisations are inherently stable and change can be difficult to effect. Technological change can provide great opportunities for business growth and renewal but a technology is less likely to be adopted if it threatens the existing identity of an organisation and its members. It is difficult to have a culture that is stable yet highly adaptable. In some cases a business can broaden its meaning to encompass new technologies, products or industries. For example, photography imaging company Fujifilm used its long history of developing and manufacturing film to become a specialty chemicals company [1056].

The adoption of new technology can be understood in terms of workplace culture and norms. For example, the medical and health care profession is slow to adopt new technologies in hospitals. Healthcare is complex, with potentially high stakes including morbidity, mortality, litigation, and public health crises, and there is increasing pressure on hospital administrators and medical staff to rationalise and standardise tasks and processes. For successful uptake of new information technology systems in healthcare institutions, the technology design must take into consideration the professional norms and values of different healthcare workers in the patient–carer network. For example, a hospital information system that requires a nurse to spend more time on the computer than with the patient may encounter resistance because patient care is the most meaningful and rewarding part of the job. Equally, from the perspective of patients and their families, personal interactions with medical staff is regarded as important. Any technology that takes the professional carer away from the patient may receive limited interest or active opposition [443].

5.1.3 Community culture and identity

The introduction of new technology creates or affects social, cultural, economic and political processes. New technology is not simply inserted into a society: it is modified, adapted and changed as it interacts with people, cultures, governance and social structures. Technology change is shaped by cultural and social groups who identify themselves by a shared set of beliefs or values e.g. churches, associations (Country Women's Association, sporting groups), clubs (RSL, Rotary), unions, peak bodies (councils, forums, alliances), activist groups (Greenpeace, anti-GMO) etc.

Studies of the Amish community – a religious group often cited for its reluctance to adopt many conveniences of modern technology – indicate that Amish people are not fundamentally anti-technology but that instead they carefully consider and regulate the use of technology to fit with their values and beliefs: hard work, community, and equality. The Amish understand that technology will impact how people live, work and interact within the family and community. For example, dishwashers are seen to diminish the value of collective work, cars encourage people to travel long distances and detach from their local community, and lighting throughout a house will disperse families throughout the home for the evening instead of encouraging togetherness and communication. The decisions made by the Amish people to reject specific technologies are heavily influenced by the potential for the technology to alter the bonds of community over time [1120] [583].

Technology itself can help shape and promote cultural identity. A study of young indigenous Australians using digital technology to create film and song found participants began to form new meaning around their cultural perspectives and identities. For example, participants reported being empowered by the opportunity to control how they are represented and to express a positive modern Indigenous identity: 'It's not up to someone else to show the way we are or control how we are seen. We are trying to do this ourselves in our own work.' Using digital technology they manipulated images and stories of themselves allowing them to control their own representation. Digital technologies have the potential to be used as cultural tools that can positively affirm identity and the place of indigenous youth in global culture [581].

Culture and identity play a critical part in the adoption and adaptation of technology. However it is important not to overstate their role. Context is not just cultural, it can be environmental, geographical, technical, gendered, political or historical. For example, in 2004 a study investigating the cultural issues concerning the uptake of digital ICT by Indigenous Australians found their low adoption of ICTs was a result of limited access to the technology due to cost, isolation, poor infrastructure and low computer skills. These factors are only indirectly associated with culture [319].

5.1.4 Technological imaginaries and collective identity

How a group imagines technology - its 'technological imaginary' - shapes how the group's members understand technology, which in turn influences how they use it. Technological imaginaries are collective ideas about technology that come from the past, help make sense of technology now, and provide insights into what form technologies might take tomorrow. Consider, for instance, an imagined future in which technology lessens or intensifies environmental challenges. Technology can be depicted as a saviour – delivering a community from environmental disaster – or a destroyer, creating potential for harm. The history of the gradual replacement of horse-based transport with electric street cars and automobiles showed that while a technological solution can be found (cities 'drowning' in manure and horse carcasses, animal welfare issues, space for stables and feed, many injuries and deaths), the solution is accompanied by environmental harms of its own. The rise of automobiles with their associated socio-technological complex involves such factors as mortality and morbidity associated with accidents and pollution, greenhouse gas emissions, and resource use. Collective beliefs can lead people either towards celebrating or disparaging the role of automobiles [558,718].

Technology can provide a way for people, groups, businesses and states to advance or frame their ideas, interests, values and beliefs. Social norms and collective history inform a group's technological imaginaries, which in turn shapes practices, regulations and laws relating to technology [352]. Digital privacy is an example. In the European Union, where personal dignity and honour are perceived to be threatened by technologies and applications which compromise digital privacy, the value of privacy shapes laws and regulations. The European Court of Justice recently ruled that Article 17 of the draft European Data Protection Regulation guarantees a 'right to be forgotten'. This requires that internet search engines prevent, when requested, certain types of personal data from appearing in search results within the EU. For example where the information is regarded as out of date, no longer relevant, or 'excessive' (although the search engine must weigh the potential damage to the person making the request against public interest in the information being publicly available before deciding whether to comply) [340,397].

In contrast, in the US, freedom of speech, freedom of expression, and freedom of the fourth estate are constitutionally protected and are powerfully supported by appeals to liberty. In many cases, appeals to liberty will trump privacy (which can be aligned with censorship). However, some US citizens appeal to liberty to protect them from state intervention and privacy invasion. In this way, interpretation of privacy in US regulation, law and social norms is based on liberty, but in the EU these concerns are based on dignity. The right to liberty in the US is associated with freedom from intrusions into personal lives by the state. In contrast the right to privacy in Europe is based on respect, personal dignity and reputation which are more likely to be threatened by publicly available information (on the internet or through the media) [1123]. Different attitudes to privacy have shaped the regulation of technologies and the interpretation of legislation in very different ways, related to powerful national and regional imaginaries.

5.1.5 Australia's national technological imaginaries

As the above examples illustrate, the way a group imagines technology depends upon its collective identity. Australian technological imaginaries are a particular case of broader Australian historical imaginaries. Australians celebrate the invention of the stump-jump plough, Victa rotary lawn mower, Ford ute and the Hills hoist. They are promoted as proud examples of Australian inventiveness and help to define a nation that celebrates innovation and adaptive re-use in a harsh (outback) environment [527].

However an examination of new technologies either adopted, adapted or developed in Australia shows that it is easy to exaggerate their particularity [46,47,307]. The pervasive legend of a peculiarly inventive country used to be typified by the 'bush engineer' who invented the stump-jump plough and the Coolgardie meat-safe. Simon Jackson, traced the legend to historian C.E.W. Bean who wrote in 1909:

> It is still a quality of the Australian that he can make something out of nothing...he has had to do without the best things, because they do not exist here. So he has made the next best do; and, even when these are not at hand he has manufactured them out of things which one would have thought it impossible to turn to any use at all. He has done it for so long that it has become much more than an art. It has long since become a part of his character, the most valuable part of it [527].

Later historians have recognised this for the legend that it is:

> The 'legend of the bush', as represented from the 1890s, is now rightly regarded as an urban myth, a romantic; construction of city-dwelling poets and novelists who inhabited one of the most urbanised countries on earth [639]

The bush-engineer legend of colonial Australian history was less of the self-taught tinkerer than is sometimes imagined:

> Australia was not reared on the shoulders of 'tinkerers and adapters' of the Manning Clark romantic myth - although that was evident in many aspects of adapting imported technology in the colonies. Rather, Australia's capacity at the close of the century to produce for itself at the opposite end of the world, and to export products and ideas, came from a considerable input of technical expertise [728].

As the 'bush engineer' myth fades, it is replaced sometimes by other parochial views of Australian technology [527,528]. Wonderful as developments such as the cochlear implant or WiFi are, there is nothing especially Australian about them, and the Australian contribution to some (e.g. WiFi) are sometimes exaggerated.

In his book *The Australian Miracle* [79], Thomas Barlow explores the influence of collective narratives. Despite a self-confessed innate inventiveness, Barlow compiles a list of myths about Australia including the first unsubstantiated claim of innate inventiveness. This process of celebrating innovation as part of a national character is not unique to Australia. Tourism New Zealand has a 'Great Kiwi Inventions' page, claiming that 'ingenuity and innovation are characteristics Kiwis are renowned for' [1051]. In 2014 the *NZ Herald* stated that 'New Zealanders have long been associated with ingenuity and a can-do attitude' [669]. The (now archived) 'Made in Canada' website observes that

> the history of patents in Canada is a story of ingenuity in response to the necessities of everyday life. It is a story of the innovative dreamers who pushed the borders of science and technology [615].

Also not unique to Australia is a national anxiety about ongoing inventiveness (with some reasonable basis in fact). Comparing again to Canada one finds analogous concerns and debate about Canadians' lack of innovative tendencies [1037], echoing Australian media, government and industrial anxieties about the extent of Australia's innovative culture [269].

New Zealand has attempted to reinvent itself as an innovating culture. New Zealand's isolation is represented as central to its culture of innovation, promoting an aptitude for local ingenuity, adaptive reuse and problem solving which are highly regarded attributes in the global technology marketplace. Despite the apparently divergent internal understandings of Australia's and New Zealand's respective cultures of innovation, a Statistics NZ report on business innovation found that innovation levels in NZ are almost identical to those in Australia [998].

The narrative a nation or collective group uses has an effect on the way they perceive themselves and others perceive them. These narratives can be reinvented. A powerful way of doing so is through skills development. Successful Australian technology development depended in the distant past, as it does now, on advanced technological and scientific skills.

> Most significantly, one pattern emerges. All successful migrant inventors came from backgrounds of strong technical education and expertise [728].

There are lessons for the present day (see Sections 7.3, 7.4):

> What then, in sum, can we derive from nineteenth century experience that is telling and instructive, and has meaning for the critical problems of technological innovation and

> development in Australia today? The most significant message is, undoubtedly, the pertinence of a strong, technically trained manpower to initiate, project and sustain technological invention and innovation; a wide distribution through the manufacturing system of engineering talent; and the presence of highly qualified entrepreneurial managers. [728]
>
> The colonies exported not only Australian primary resources, but also high value-added goods. There was a clear absence of an attitude that has now become deep-rooted, that Australian innovation is fully recognised only when it has been exploited by industry abroad. Nineteenth century inventors and entrepreneurs demonstrated an assertive technological approach. [728]

As has been the case in the past, Australia's future with new technologies will continue to be informed by its national technological imaginary. Reinvigorating Australia's technological imaginary through investment in tinkering skills, scientific education and inculcating an attitude of experimentation and global confidence can accelerate Australia's technological future (Sections 7.3, 7.4).

5.1.6 Meanings and attitudes can change over time

Just as identity and imaginaries are not uniform and are changeable, attitudes to technology are shaped and reshaped, particularly in how people interact with technology. Many near ubiquitous modern technologies were initially met with fear. The case of automation provides some salient examples.

The idea of autonomous technology – technology that does what it 'wants' independent of human direction – has long been a source of both keen anticipation and anxiety [1136]. In the 1950s and 1960s automated cars on automatic highways were popular predictions. Futurists expected that driving would become more passive: dream cars would allow owners to watch TV or catch up on work as they travelled around the city. As Americans were being enticed by automation in their cars, homes and public transport, they were anxious to see the effect automation would have on their jobs and happiness [211] (Appendix C.3, [931]). The introduction of automation, artificial intelligence and robots in the workplace is often associated with fears of widespread unemployment. However there is no evidence to suggest technological change is a cause for long term decreases in employment (Appendix C.7, [868]).

Attitudes to automation and robots are complex. In general, people are relatively comfortable adopting automated machines when there are clear and immediate benefits to be gained in safety or convenience. People have accepted many automated and automatic technologies in their everyday lives. In the early 20th century these included the automatic toaster, elevator doors and traffic lights; mid-century, the automatic kettle, car airbags and automatic trains (London Underground); late 20th century, anti-lock brakes on cars and robotic surgery. Automation has been slowly introduced into cars since the early 1900s. Every decade since the commercialisation of the automobile more automation has been introduced gradually, it quickly begins to feel just like a natural part of driving [576].

Aversion to automation and robots may stem from fear about their agency or the consequences of mechanical failure. But it may also derive from literature and films or lack of understanding of what the robot can do. Robots have been used in industrialised manufacturing since the 1960s. Lower costs, miniaturisation and the diversified interests of a consumer market are now facilitating their entry into other markets and locations such as the home. Here, they operate in more intimate, personalised contexts, designed to assist with daily mundane activities such as cleaning, care, health, and entertainment. This increasing pervasiveness suggests that once people gain insight into the point and purpose of a technology, when it becomes personal or domesticated, it becomes less threatening. Once the novelty of new technologies has worn off they become mundane in everyday life (Appendix C.6)[540]. People personify their cars and smartphones, often attributing a kind of agency to them, without fearing they will transmogrify into robot overlords. A Roomba is an autonomous robotic vacuum cleaner that senses and responds to the environment. In doing so, it has been imbued with human characteristics and features in popular YouTube videos and the @SelfAwareRoomba has 23,900 followers on twitter (Appendix C.6)[540].

New automated technologies have enacted a shift in how people conceptualise robots. For example Siri is an automated device that 'listens' as well as talks back, allowing potential for development of a relationship. Technology with the capacity to listen offers the potential to develop not only new consumer markets but also shift how people think about robots in everyday life (Appendix C.6)[540]. A *New York Times* article written by Judith Newman in 2014 describes the benefits of the relationship her 13 year old autistic son, Gus, has with Siri. Siri responds to Gus's many questions without frustration. To get a relevant response from Siri he must enunciate clearly, which has led to an improvement in his speech. Newman believes Siri is a great communication tool for someone who does not pick up on social cues.

Siri makes Gus happy. She is his sidekick. Last night, as he was going to bed, there was this matter-of-fact exchange:

> Gus: 'Siri, will you marry me?'
> Siri: 'I'm not the marrying kind.'
> Gus: 'I mean, not now. I'm a kid. I mean when I'm grown up.'
> Siri: 'My end user agreement does not include marriage.'
> Gus: 'Oh, O.K.'[763].

Meanings, values, worldviews, identities and beliefs persist, but they are nevertheless not static. They all inform and are shaped by collective and individual experiences of technology. While attitudes to technology emerge from existing meaning and values, attitudes are both shaped by and influence experience.

5.2 Attitudes to technology

There is no simple relationship between attitudes and technology. Attitudes to technology cannot be meaningfully understood in isolation from the social situation in which technology is being used. The technology, the user, the social structure, the environment, all play a role in how technology is developed, experienced and modified. Attitudes are not individual: they are derived from a social and cultural context. Individuals hold attitudes in association with their values, usually having some connection to family, peers, profession, location or special interests, and experiences [875].

All individuals and groups inventing, evaluating, using and adapting technology are driven by meanings, attitudes, beliefs and values (their own and others, real and perceived). Governments and regulators are often influenced by perceived public attitudes to technology. This is particularly evident in the way Australia, with other countries, have chosen to regulate genetically modified organisms (Box 14) (Appendix C.4, [932]).

> The Swinburne National Technology and Society Monitor survey, an annual study performed since 2003, indicates that in 2013 most Australians surveyed were comfortable with what they perceive to be the rate of technological change. Some technologies were shown to polarise the community– stem cells, nanotechnology, and genetically modified crops and animals, for example. Most Australians surveyed are very comfortable with having wind farms and somewhat comfortable with 'clean coal' (carbon capture and storage). But most Australians surveyed are not comfortable with coal seam gas, unmodified coal use, or nuclear power plants in Australia. The study found that Australians strongly support government regulation of new technologies, and those people who are more likely to trust science organisations and professional institutions are also more accepting of the introduction of new technologies [144].

Box 14: How do Australians feel about technological change?

It is difficult to predict the attitude a person will have to any given technology, and whether or not a technology will be adopted. Attitudes are complex, and are formed from collective and individual values and beliefs in cultural, social and professional settings. To gain a better understanding of how people think and feel about technology it can be useful to look past the technical and functional properties to the social context that produces them. Attitudes and decision to adopt may be based on the technology itself (the artefact, design or process) or the impact of the technology, or its perceived or potential impacts in combination. People may express concern about how the adoption and use of the technology will change their everyday life and experience. The degree to which new technology is understood and experienced can also affect the level of uncertainty felt, and contribute to the way in which technology is assessed for both risk and benefit.

5.2.1 Choosing to adopt or resist technology

In its simplest form, attitudes toward technology change and the adoption of technology can be considered in terms of adoption and resistance. The choice to adopt or resist a technology can be made for many different reasons, and enacted in many different ways. Resistance to technology is not new and is often most visible when activist, lobby, advocacy, consumer or industry groups oppose or seek to influence technology development or implementation. There are many examples of active resistance to the introduction of new technologies, some of which are outlined in Table 2.

Technology / innovation	Description of resistance
Information and communication technologies	General concerns were expressed that the Royal Post and the US Postal Service would endanger privacy and confidentiality. There are now similar concerns with the rise of the internet, mobile telephones, and pervasive electronic social media. These concerns seem somewhat vindicated in light of the Snowden revelations about PRISM, and the complicity of many national security agencies.
Safer designs	Pilots rejected the 1961 Cessna because it was deemed too safe and easy to fly by male pilots. Similarly some early bicycle designs were rejected because they did not fit with contemporary ideals of masculinity [805].
Recycled water	In 2006, when Toowoomba held a referendum on the use of recycled water for drinking, 62% of residents were opposed. Once the proposal was made, an activist group, Citizens Against Drinking Sewage, used the 'first mover advantage' to promote the 'yuck' factor and fear of health risks before the council could disseminate information to the community. Failure of the recycled drinking water plan was attributed to public opposition as well as to politics, timing, vested interests and information manipulation [514].
Genetically modified crops	Despite extensive scientific evidence supporting no adverse health effects from GM crops, strong opposition to genetic engineering by activists and the general public has resulted in heavy regulation of the technology. Activist groups in Europe have been particularly effective, using discredited scientific studies and strong imagery and language to promote their cause. The intensive and time consuming regulation required for GM crops has been criticised as unnecessary by scientific experts and governments around the world (Appendix C.4)
Smart meters	Stop Smart Meters Australia is a citizen group lobbying for the removal of smart meters from households. 'Smart meter refugees' claim headaches and sleep deprivation once a smart meter is installed in their home. Although some people may be sensitive to emissions of electromagnetic radiation, testing shows that smart meters emit less than a baby monitor, mobile phone, operating microwave oven, or laptop computer [500].
Wind farms	The introduction of wind farms has led to complaints of health problems perceived associated by the complainants with exposure to wind turbines. In 2013 the NHMRC commissioned a review on the health impact of wind turbines. In summary: 'the' evidence considered did not support the conclusion that wind turbines have direct adverse effects on human health. Indirect effects of wind farms on human health through sleep disturbance, reduced sleep quality, quality of life and perhaps annoyance are possible' [678].

Contraceptive pill	The feasibility of the male pill was demonstrated in the 1970s and yet it is still not widely available. Contraception predominantly remains the responsibility of the female. Its acceptance, or rather its rejection, can be understood to be less to do with its technological availability than changing ideas around reproductive responsibility [801].
Numerals in phone numbers	In the US in the 1960s an anti-digit dialling league was set up in San Francisco when Pacific Bell switched from name+ + numerals to numerals-only in the phone number. 'When Bell System executives grandly announced that all telephone exchange names would soon be replaced by seven-digit numbers in the name of progress they presupposed the blind acceptance of a benumbed and be-numbered public. They were wrong: the telephone company is now facing a minor rebellion. In San Francisco last week the Anti-Digit Dialing League was incorporated to oppose "creeping numeralism"' [1047].
Vaccination	Anti-vaccination campaigners continue to fight against childhood vaccination despite scientific evidence of efficacy and safety. Despite the attention given to parents who refuse to immunise their children, in Australia the vaccination rate for children 5 years of age and above is 90% [274].
Consumer resistance	In 2009, Kraft released a Vegemite-cheese blend based on a common user modification of its popular Australian spread. The new product was marketed as iSnack 2.0 after intensive market research, seeking to capitalise on Apple's marketing success and position the product as high tech. Less than a fortnight after the name was chosen, Kraft was forced to change the name to Cheesybite, faced with a public relations disaster on a scale rarely experienced in Australian marketing.

Table 2: Some examples of active resistance to technologies

Table 2 suggests that resistance to technology is motivated by disparate influences that are not always obvious to outsiders. For example, a person who prefers to work visually might enjoy manipulating an image on a computer screen but be uncomfortable using a computer as a word processor. It might appear irrational or illogical to an outsider that a person is willing to use the computer for one function, but not another [805]. It is the use and application of the technology in a particular context – a given person, time, place, process – that determines a person's experience, rather than solely the artefact or process itself [163] [663] [798]. Meanings and personal experience co-exists with objective approaches to decision making and attitude formation. They all play a role in the choice to adopt technology (or not), or to use technology in a particular way.

Biotechnology has created great public debate in recent decades. In the mid-1990s, the movement against genetic engineering gathered strength, particularly in EU countries including France and Great Britain. In 1996 agricultural biotechnology company Monsanto introduced genetically manipulated soybeans to Europe without labelling them as such. Activists jumped on this apparent attempt to conceal the origin of the product, using Monsanto's lack of disclosure as further evidence of the power and manipulation the company exerted [948]. Monsanto and other proponents of GM food claim that as there is no danger associated with their product, there is no reason to label it. So resistance and promotion of technology choices must be understood in terms the meanings and values associated with biotechnology (refer Section 5.1) (Appendix C.4, [932]).

Attitudes to technology must also be considered in terms of environmental and social context. Recycled drinking water was rejected by the people of Toowoomba in 2006, but a more recent Queensland study found that people may be more open to the idea when the local area is experiencing severe drought [357]. Similarly, the more favourable attitude toward genetically modified crops in developing countries has been explained by the urgent need for food and for improved nutritional content. Recent research has found that social context is crucial to understanding uptake of energy technology and that consumer research should examine personal values and the emotional bond between people and their environment [983] [279].

Thus context – both social and environmental – can play an important role in how receptive people are to accepting new technologies.

People have different motivations that drive their decision to engage with a technology and to the degree on engagement. The use of the internet is becoming more necessary to participate socially, politically or bureaucratically. Understanding the attitudes of those who, by choice or opportunity, do not use the internet can help support digital inclusion [1111]. Accounts of non-adoption of ICT can represent non-use as 'abnormal' and work on the assumption that ICT is inherently desirable. However people will have legitimate reasons for not engaging with ICT. In fact, the main factors found to determine internet use include age, income, education, Indigenous status, affordability and availability of infrastructure. At the same time more complex issues identified include skills, confidence and trust [10]. Any government policy aimed at addressing inequalities in internet access and use must acknowledge the different reasons people choose to engage [232,1111].

Tinkering can also be seen as a mode of resistance to the existing form of a product or to the use intended by the original designer. People who tinker with technology may resist, reject, or use a device or service, or find different uses for the same device or service. Tinkering can involve getting inside a closed system ('into the black box' or 'under the hood') to understand or change the inner workings of a technology [1106], (Section 5.3.3, Appendix C.9).

Some people will build technologies for the sheer pleasure of it, and desire for novelty. This is not a modern phenomenon: Otto Mayr, writing of Heron of Alexandria (1st century A.D.), said 'Heron display[s] a certain delight in the pure principle of this invention, a delight that seems independent of practical use and commercial profit', page 26 of [659]. Heron himself understood the desire for novelty for its own sake: 'Furthermore, one must avoid the predecessors' designs so that the device will appear as something new' ([659], page 20). The importance of creativity in encouraging engagement with new technologies is explored in detail in Section 7.3.

Closely related to creativity is curiosity [628] which underpins technologists enthusiasm for new technologies [429,503,1093]. Being a creator of technology leads to specific attitudes to technology and even within this group there are differential attitudes to technology. For example, men's and women's attitudes to the creation of technology differ. A key factor for 'men's love-affair with technology' is said to be related to the *mastery* of a complex skill [569], but like most attitudes, the story is rich and complicated. In general, men's attitudes to technology can differ from women's. As Ruth Cowan Schwartz has put it 'we do not usually think of women as bearers of technological change… We have trained our women to opt out of the technological order as much as we have trained our men to opt into it' [218]. There are differences between men and women's approaches to mastery, not least in how they express it [1061,1109] (page 105). Turkle illustrated this difference by the example of a female computer science graduate student's articulation of her attitude to creating new software), where she viewed the technology as 'language' not a 'machine'[45].

> I hate machines. But I don't think of computers as machines. I think of moving pieces of language around. Not like making a poem, the way you would usually think of moving language around, more like making a piece of language sculpture [1061] (page 112).

The student's apparently contradictory attitude – she 'hates machines', but likes creating software (a technology) – is not uncommon when examining anyone's attitudes to technology. Gender-based attitudes to technology creation are far from simple and attitudes are but one

[45] In doing so the student recapitulates the history of the development of computing technology, which progressed enormously precisely when this connection with language was identified [770].

factor in people's enthusiasm to embrace new technologies [488][46]. However attitudinal differences between genders are a significant reason why so few women (in Australia) wish to become technologists [349,424] given the substantial contribution of women technologists [995]; see Section 7.3.

5.2.2 The role of language

Language has an important part in technology, its invention, construction, and implementation. The language chosen to describe technologies influence the way people think about technology, how they incorporate technology into their lives, the stories that are told about them and the ways they are experienced.

Certain words can carry negative connotations – companies seek to label their products 'chemical-free', even though it is a meaningless designation, as everything contains chemicals. Anti-GM activists created alternative frameworks through the language used to influence how consumers would interpret and understand new biotechnologies – using the term Frankenfood, for example, evokes the Victorian grotesque of Mary Shelley's abomination in a deliberate attempt to induce fear and revulsion (Appendix C.4, [932]). The US Defense Science Board Communication has released a report addressing the use of the word autonomy, concerned that it can evoke images of computers making independent decisions and taking uncontrolled action. The Board argued the design and operation of autonomous systems would be better expressed in terms of human–system collaboration, which has the additional virtue of downplaying machine independence [257].

Other words, phrases and concepts are typically associated with healthfulness and virtue. The 'appeal to nature' fallacy refers to the belief that natural things are innately good and unnatural things are innately bad. Of course not all good things are natural and not all natural things are good (for example, the clean water derived from water filtration is widely considered to be a positive public health intervention; cholera, which occurs naturally in water sources, makes people sick). Some opponents of GM crops claim that GM food is dangerous because genetic modification is unnatural, and that conventional or organic crops are in contrast beneficial. This view ignores the mutational load of conventionally bred crops, which over time are genetically modified (Appendix C.4, [932]).

The way people categorise, think about and talk about technology has implications for attitude formation and decision-making [131]. Although categorisations and labels provide useful mental shortcuts and may help industry and regulatory bodies, general categorisations can be problematic. The use of broad categories – such as biotechnology, nanotechnology – can mask the history and development of the technology as well as oversimplify what it means and how it will be used. Blind to the disparate histories of nanotechnology's parts, potential users, developers, policymakers, and regulators may fail to consider whole suites of products or processes on their merits, instead assessing them with unwarranted optimism or pessimism, depending on their attitudes to the umbrella category 'nanotechnology'. On the other hand, there is evidence that many people, when presented with sufficiently nuanced information about broad technology categories, can make reasonably sophisticated distinctions between specific applications and associated risks and benefits [525,526].

5.2.3 Trust in technology

Trust is significant for all aspects of technology. The issue of trust becomes important because of the meanings associated with technology and the uncertainty surrounding technology

[46] Disentangling the historical question why there was 'more work for mother' (through the development of household technology goes beyond attitudes; likewise sex-differences in technology *use* are not solely due to attitudes [219,709,729].

change. To generalise, it is likely that trust diminishes when people feel a loss of control, power, or understanding of technology.

When information is limited, complex or contradictory, people tend to make judgements driven by values and beliefs rather than the information provided. When there is little information on a new technology and people cannot assess possible risks, trust in institutions becomes more influential [893]. Studies investigating the Australian public's attitude to specific technologies frequently cite trust as an important factor in predicting the acceptance of new, complex and controversial technologies [209,225,526,579].

The annual Swinburne National Technology and Society Monitor survey finds that Australians express most trust in the CSIRO, universities and hospitals. They are somewhat trusting of scientists, small business, environmental movements and the public service. There is a low level of trust in governments, churches, large companies, trade unions or the media. Results consistently show that people who are more likely to trust science organisations and professional institutions are also more likely to accept new technologies [144]. Given the expressed trust in scientists and the public service, the scientific community and regulatory agencies have an opportunity to promote confidence and trust. Regulatory bodies play a key role, ensuring necessary guidelines are in place to manage health and safety concerns. Accurate information and effective communication are also important mechanisms to developing trust (see Section 5.3.4).

Temporary changes in levels of trust in a given technology can occur when controversial events occur– trust in nuclear energy, for example, can change when a nuclear plant accident occurs. But such controversial events have been shown to be less important and less persistent in shaping attitudes to technology than stable pre-existing beliefs [938]. For example, although perception of the risks of nuclear power have been shown to temporarily increase after an accident like Fukushima, pre-existing attitudes toward nuclear energy remain a more important predictor of nuclear energy acceptance [1099].

Box 15: Risk perception and pre-existing attitudes, using Fukushima nuclear power plant as an example.

Conditions of trust can vary for different technologies. For example, trust in medical technology works differently to trust in other technologies. The unique feature of medical technology is that a human patient is the subject being acted upon and the role of the human in this system is likely to heighten the importance of trust. A small US study investigating human conceptions of trust in technology found participants think of trust in three ways:

1) Actions that a person performs when they trust technology e.g. purchasing and using technology
2) Feelings about a technology e.g. believing in the technology and feeling comfortable with it
3) Characteristics of the technology that lead to trust (or distrust) e.g. reliability, being easy to use.

These categories may be a useful way to understand the difference between trust as a belief system and trust as a product of the technology's performance [713].

5.2.4 Judging risk and making decisions

People faced with uncertainty look for ways to make sense of unexpected and unknown events. When estimating the likelihood of an event, people make their judgements based on the information most easily accessible (referred to as the availability heuristic). For instance, when an infrequent event is brought easily to mind, people overestimate the chance that an uncommon yet memorable event will be repeated. For example, after the attack on the World Trade Centre on 11 September 2001, there was an 18% decrease in domestic flight travel in the US. While some of this was due to increased security and inconvenience, some was due to fear of further attacks. As a result, more people chose to drive long distances. By doing so, they were actually placing themselves at an increased risk of injury and death from personal vehicle-related accidents [717]. People are most likely to use intuition over facts when deciding potential risk.

Psychologists believe that many biases serve an adaptive purpose because they allow people to reach decisions quickly. However, they can also lead to cognitive bias – systematic deviations from a standard of rationality or good judgment. Cognitive bias can influence how information is understood, how risk is perceived and consequently how technology is developed, judged (Box 16) and regulated. No individual, group or profession is immune to cognitive bias. Bias can influence decisions made by scientists and engineers in their prediction, development and assessment of technology, and at all stages of research and development, risk assessment, and cost-benefit analysis. It affects how individuals, businesses and governments process information and assess risk, and how the media presents information. Cognitive bias plays an important role in how people assimilate information so that the world they live in makes sense to them.

Risks and their perception

Roads: In Australia, 1,193 people died on the roads in 2013[121]. In the same year, 1,920 people died as a result of accidental falls[8] but and only two people died from shark attacks [48]. Many people will refuse to swim in the ocean for fear of shark attack, but will blithely drive their car to the beach, and may well fall off the rocks.

Death in the newspaper: In one of the first studies of media coverage of risks and public perceptions, two US newspapers were analysed for the number of times they reported various causes of death. The study found although diseases (including for example diabetes and cancer) accounted for almost 100 times more deaths than homicides, there were about three times as many articles about deaths from homicides than about diseases. Many statistically frequent causes of death were rarely reported. [197,973].

Box 16: Risks and their perceptions. See also Table 6 in Section 6.4.2.

The automatic tendency to notice or give more credence to information that confirms existing beliefs is referred to as confirmation bias. This affects assessment of risk. For example, pro-vaccination messages were found to be least persuasive for those parents with the most negative attitude to vaccines. Researchers found the evidence-based material presented to those parents actually hardened their anti-vaccination views, in a form of cognitive bias often labelled the 'backfire effect' [774]. Similarly, a US survey exploring exposure to information about the risks and benefits of nanotechnology, and attitudes to it, confirmed that people tend to select information that supports their existing beliefs. In some cases, receiving additional information only served to further polarise opinions [543]. Assimilation of information about genetically modified foods and about global warming depends heavily on prior beliefs, cognitive bias, illusory correlations and prior knowledge [664]. Common information can result in great differences of opinion between people, because the interaction of personal values and the decision-making tools people employ affect their reception and understanding.

Techniques for presenting information are important to make it possible for people to make informed decisions. Food labelled 90% fat-free, for example, is more appealing to diet-conscious consumers than food labelled 10% fat content [548]. The framing of information for different audiences can strongly influence risk assessment, decision-making and understanding (a cognitive bias known as the 'framing effect'). In 2009, there was a significant difference reported between uptake of the influenza H1N1 vaccination in Sweden (60%) and Australia (18%), even though both countries offered similar childhood and adult vaccination programs. Communication plans in both countries used information recommended by the World Health Organisation for the media and public. The information included assessment of the situation, and information on risks, symptoms, modes of infection, what people could do to protect themselves, what the government was doing, availability of medication and information, and how to respond to infection. Australian studies found the main barriers to uptake were perceptions that influenza was not a serious condition and that the vaccine caused complications or side effects. The study found the Australian communication plan underplayed risk, used vague and basic wording in instructions, and did not address the uncertainties associated with the vaccination programs. By contrast, the Swedish plan included information on how to respond if the media provided unsubstantiated information, enabling health professionals to deal quickly with misinformation [933].

'Zero risk' bias refers to the tendency to prefer the appearance of the elimination of any risk. Because emerging technologies are new and unfamiliar their uptake is often impeded by the expectation that they should pose little to no risk. For example the American federal policy (the Delaney clause) outlawing cancer-causing additives from foods (regardless of actual risk) was focused on complete risk elimination. The effort needed to implement zero-risk laws has grown as technological advances enabled the detection of smaller quantities of hazardous substances [590].

All options in life, including current technologies, carry some risk, e.g. conventionally grown crops, fluoridation of water, immunisation, pasteurisation of milk, conventional medicine. Zero risk bias is often acted out in appeals to the precautionary principle. The precautionary principle is prevalent in contemporary information technology and biotechnology policy debates. The principle is often interpreted as mandating that since every technology could pose some theoretical danger or risk, public policies should prevent people from using innovations until their developers can prove that they would not cause any harm. In fact all the precautionary principle requires is that if an action or policy has a suspected risk of causing harm, the burden of proof that it is not harmful falls on those taking an action (in the absence of scientific consensus that the action or policy is harmless). It encourages discretion, not inaction, because of course there may be no more risk in advancing without caution than there is in delaying new options [870]. For example, in the face of increasing evidence that coal-fired power contributes significantly to the greenhouse effect, a balanced cost–benefit analysis might consider the comparative advantages and disadvantages of nuclear power.

With the expectation that new and emerging technologies should have little or no risk, status quo bias may take hold. Status quo bias refers to risk aversion which manifests in a tendency to look for a sure gain before taking a risk. Potential losses and disadvantages are weighted more heavily by people subject to status quo bias than potential gains and advantages of a system (loss aversion). Loss aversion may be associated with a strong preference to maintain the status quo [546]. Cognitive psychologist Daniel Kahneman suggests that any one option becomes more popular when it is presented as the status quo, and the advantage of the status quo option increases with the number of alternatives presented [546].

It is common for forecasters to be seduced by technological wonder and self-interest and suffer from optimism bias, which causes them to lose perspective of other considerations [941] (Appendix C.3, [931]). This phenomenon is called optimism bias. When evaluating any given project, optimism bias and strategic misrepresentation can lead to overconfidence. People underestimate costs, completion times and risks but overestimate the benefits. The technique of reference-class forecasting is an approach which can reduce the effect of optimism bias and strategic misrepresentation in organisational planning. Starting from the position that more accurate assessments are usually obtained from people who are not directly involved in the project, reference class forecasting takes an 'outside view' [546]. It aims to improve forecasts and assessments by requiring decision-makers to identify a relevant and similar class of project for comparison, use credible and empirical data with which to make statistical conclusions, and place the project in a statistical distribution of outcomes from the class of similar projects [369] (Section 6.4.2). Being aware of cognitive bias is not in itself enough to reduce its influential effect in decision making. Some strategies to overcome bias in organisational decision-making include training individuals in statistical reasoning, making people accountable for decisions made, and delegating decision-making to groups rather than individuals [691].

Nobody – researcher, engineer, technologist or any author of this report – is immune to the biases described here. The same facts about a scientific phenomenon or a technology can mean different things to different scientists depending on their own values and beliefs. Also, frames of reference will differ for researchers depending on their place in the technology lifecycle. For example, when assessing medical technology, a researcher associated with the development of technology might be more concerned with superior technical features than a researcher involved in the clinical trial stage, who will be more concerned about patient safety and comfort [399].

All people hold cognitive biases which affect how they process information; expertise does not shield a person from the effects of their personal values, preconceptions, and social and cultural contexts. Risk assessment, reasoning and decision making all exist in union with the meanings people have about technology. Attitudes are formed through meanings and cognitive forces. They both shape how problems are posed, how information is sought, and the methods and criteria used for evaluation by all decision-makers (Section 6.4.2).

5.3 The way people interact with technology

To this point the chapter has discussed the contribution of meaning, values, belief and attitude to the way people feel and think about technology. User experience, social practice and how people communicate about technology are also important facets of the interaction between people and technology. Social structure and context shape how people use and modify technology, and the uses of technology shape its social context.

5.3.1 Behaviour often does not reflect attitude

As influential as attitudes about technology are, how they translate into actions and behaviour is complex. People's behaviour with technology can be at odds with their fears and concerns. A survey of Australian attitudes to nanotechnology found that while there was widespread agreement that product labelling should provide information about any nanotechnology used, few respondents said they always read labels of products [526].

The issue of privacy and security is another area where attitudes do not match practice. As people increasingly engage online for commercial and social reasons, the way people understand privacy and security is being challenged. The highly public debate about online privacy and security does not discourage most people from using the internet. A study by the World Economic Forum found that internet users worldwide believe that the internet supports freedom of expression and should support privacy – most hope that governments will protect them from harm without undercutting the value of the internet [315]. There can be a disconnect between the people who design security systems and the people who have to use them. If a system of protection is complicated to use, people will avoid it, even if they're aware of the dangers of doing so.

Similarly, even though people express concern about environmental sustainability, there is a mismatch between the consumer's expressed desire to support renewable energy technologies and their actual willingness to purchase these products. A study by the Dublin Institute of Technology investigating the attitude–behaviour gap in the context of renewable energy found that adoption is expected to increase with lower costs and continued reinforcement of the need for sustainable energy [778]. Much of the existing consumer research in the area of renewable energy is based on regulatory, financial and information impact on consumer choices. However, more recently, researchers have found that social context, personal values and attitudes are crucial in understanding consumer behaviour. Future research into behaviour will need to go beyond cognitive assessment and explore the social and cultural dynamics that underpin individual responses [983].

A study in the US investigating the claim that the public is increasingly anxious about the safety of childhood vaccinations found that for almost all the public, vaccine risks are actually not a concern and vaccination rates are high. Similarly, in Australia the percentage of children fully immunised at ages 12–63 months is high, ranging from 89.7% to 92.5% [274], despite the activity of anti-vaccination groups and the air-time accorded them by sections of the media.

Box 17: Perceived negative attitudes to immunisation are not always reflected in behaviour.

5.3.2 Understanding changing social practices and norms

User experience, local culture and social practice are important factors in a person's decision to engage with a technology. This approach has been helpful in health and reproductive technology, which often involve deeply held ideas of personal, religious and cultural identity. For instance, health experts working in the Philippines were able to promote the contraceptive pill more effectively when they found villagers understood that when their hens ate the seeds of the iping-iping tree they stopped laying eggs. Explaining that the contraceptive pill worked in a similar way helped the community come to terms with this new innovation [894]. Achieving closer contact between the user and those who design, build and promote technology has been demonstrated to increase uptake and adoption and is known as a 'convivial' way of practicing technology [519] [805].

Social and professional norms are behaviours and cues within a group that guide action and behaviour in direct and indirect ways. The use of technology can shape or modify social practices and norms associated with a technology. For example, email supports workplace flexibility and autonomy, but it has had complex and contradictory outcomes for professional clerical workers. The rise of mobile platforms has been accompanied by a wider change – electronic social media including email now provide a means by which people keep in contact socially and domestically as well as professionally. So the use of email outside the office is a consequence of a wider shift of professional/domestic boundaries and a revolution in distance communications. Office workers have long brought their work home, or stayed in the office late. Email and mobile platforms potentially allow greater workplace flexibility and effectiveness, while adding the ability to keep in touch with friends and family as well. Studies in Australia show that using email outside the workplace is now common practice [384] [837].

Just as changing practices can influence social environment, changes in social environment have been shown to influence behaviour and practices. This idea has been exploited by governments all around the world in the form of social norms campaigns which extend ownership of a particular problem from the individual to the broader society. Such initiatives are believed to be very effective in changing social norms and practices in relation to the uses of technology. For example, the *Pinkie* campaign in Australia aimed to reduce speeding on roads by young males; it used humour and ridicule to do so [999]. Similarly, *Coolbiz* in the UK encouraged business people to wear cooler clothing in summer (instead of traditional business attire) so air conditioners were not required to be set so low in work buildings, supporting energy efficiency [882]. For some social policy problems, influencing human behaviour is very complex and requires ongoing commitment as demonstrated in Australia's approach to tobacco control. The comprehensive and long-term approach used by the government included an extensive range of mechanisms (regulation, legislation, taxes, sanctions, community support, services, education etc.) to change social norms, and has been credited with the continued decrease in national smoking rates [51].

Increasingly, behavioural insights are being used in government policy interventions. Behavioural insights are based on the premise that people make predictable mistakes in their decision making (Section 5.2.4). 'Nudge' initiatives change the way decisions are framed and use positive reinforcement to influence decision-making. In addition, nudge initiatives provide normative information which informs participants where their behaviour lies compared to the measured norm of a wider group, because most people overestimate the prevalence of undesirable behaviour and use their perception of peer norms as a standard to compare their own behaviour with. Many policy interventions based on behavioural insights are relatively simple and cheap and are used in combination with traditional policy levers, such as regulation, tax and subsidies (Chapter 7).

5.3.3 Tinkering as a pathway to innovation

Tinkering is a socio-technical, material and cultural practice; an investigative do-it-yourself (DIY) approach to invention. It is an ongoing process – people tinker with problems, ideas, clothing, cooking recipes, cars, broken toasters, mobile apps and software, mobile phones, furniture, and more. Tinkering has no preconceived or defined end. To tinker is to test, experiment, make mistakes and keep trying. As such, it is seen as a valuable skill for innovation.

Tinkering is a creative practice that can be applied to any pursuit. It has the potential to affect a range of Australian businesses from community and small-scale business to large-scale manufacturing. Tinkering is an important component of science and engineering. As a social practice, tinkering may be a useful way to renegotiate how Australian people and businesses relate to science and technology: tinkering shows adaptability to changing circumstances and uncertainty; such skills are highly regarded in commercial and manufacturing contexts and useful in technology uptake. And failure is redefined in the practice of tinkering. Failure does not mean the death or end of a project but rather is part of the innovation process and can reveal new ways of thinking about a problem (Appendix C.9, [542]).

Fear of failure or ridicule can be a serious impediment to innovation (Section 7.5). If schoolchildren are encouraged to experiment by tinkering, they learn that failure is not an impediment, but a routine legitimate part of the process of solving a problem. People can be taught to tinker – the ability to do so is not innate.

5.3.4 Attitudes, beliefs and values and effective technology communication

To this point the chapter has explored what technology means to people, how attitudes are formed and how people choose to engage with technology. How people understand science and technology is key to all of these issues – the availability of information, the language used, the way information is presented, the level of trust associated with its source. This leads to the broader question of what Australian policymakers and technology actors need to do to ensure that a much broader cross-section of Australian society understands technology and engages in technology issues.

Science and technology have often been seen as the preserve of scientists, technologists, policymakers, and those with a perceived expertise in technical matters. Over recent decades there has been an intensification in activities which aim to improve the relationship between people and science and technology. In the field of science communication, scientists, universities, science and research agencies and science advocates have worked hard to present their work to different audiences, telling stories about science and about being scientists.

Despite all the efforts made to improve science communication, there is limited evidence to indicate that scientific literacy leads to greater trust in science [692]. There is now a considerable literature about public understanding and engagement in technology, in which values and beliefs provide important context for evaluation, decision-making, policy development and adoption of technology [353,601,739]. Paying attention to the meanings of technology to all people is an important tool for understanding, documenting, and analysing the typically diverse and contradictory views about technology, and the practices people associated with technology.

Various groups have different attitudes, opinions and beliefs. A target segmentation strategy which includes tailored messages for people from different social backgrounds and with differing world views can improve communication [495,543]. Attitudes to technology are not formed in isolation – individuals hold attitudes linked to their values which usually have some connection to a social group and a source of authority. Typically, information communicated in small groups can address denial of evidence much more effectively than mass communication received in the privacy of one's living room [771]. Effective communication about technology has a foundational role to play for all in society.

Science and technology communication involves everyone and needs to include discussion, listening and engagement across the whole of society. It is important to understand that the 'public' is a diverse collection of people with different levels of knowledge, values, beliefs, world views and cognitive models, and that it includes scientists, policymakers, industry leaders and politicians. Paying attention to the meanings of technology is an important tool for understanding, documenting, and analysing the typically diverse and contradictory views about technology, and the practices people associated with technology.

In a democratic society like Australia, there are expectations, customs, and rights for citizens to participate in public policy and have input into the issues that affect them. Improving democracy and public participation in relation to technology holds promise for addressing the common perception that the public does not understand technology, and that, possessed of such ignorance, the public typically 'resists' the introduction of technology. Community support for the development of wind farms, for example, has been shown to strengthen when advocates use community engagement processes [463]. All actors in the network can engage in ways that enhance transparency and local support, and complement formal regulatory processes. Group discussion of complex technological issues can help individuals develop their own views and can be an appropriate setting in which the public can provide valuable information to policymakers, researchers and industry [308,1003].

5.4 Meanings of technologies matter

The meanings people associate with technology can strongly influence what kinds of technology are invented – how they are designed; which technology is adopted, and for what purposes; what the political, economic, social, and cultural implications of technology are; how technology is predicted, assessed and governed; what kind of innovation system and culture a country has when it comes to technology; and how people can put technology to best use. Acknowledging the complexity of meanings, values and attitudes in the way people experience technology will help to explain patterns of resistance to and acceptance of technology. The choice to adopt or engage with technology cannot be simply reduced to resistance. Resistance can take many forms and the reasons can be complex and nuanced.

When there is little information on a new technology and people cannot assess possible risks, trust in institutions becomes more influential [893]. Studies investigating the Australian public's attitude to specific technologies frequently cite trust as an important factor in predicting the acceptance of new, complex and controversial technologies.

It is difficult to find studies that consider the full range of broad, varied, and sometimes conflicting phenomena that contribute to people's experiences of technology. One way to understand attitudes and behaviour is from the perspective of cognitive psychology. This field provides a means to evaluate and measure decision-making processes and the mechanisms that influence acceptance or rejection. Other disciplines such as science and technology studies, anthropology, sociology, and media and communication studies seek to understand how users associate particular meanings with particular technologies and their use, and how these meanings are shaped by experiences. Despite the challenges, a multidisciplinary approach that brings together all of these different perspectives to consider how people feel about, think and talk about, and use technology can contribute a meaningful study of technology prediction, adoption, use and impact.

Providing information and facilitating deliberation can effectively increase public familiarity with technologies and allow better understanding of the broader impact of technology. Social media and other digital communication can help provide accurate and up-to-date information

Australia needs to adopt a more inclusive approach to understanding technology, by openly acknowledging and debating meanings to help shape Australia's future technological choices.

6 Evaluation

Summary

Since cost is a major determinant of technology adoption, the evaluation of technologies is central to the process of adoption.

Cost-benefit analysis is the best starting point for technology evaluation and there are transferrable lessons to be learned from the use of cost-benefit analysis in the evaluation of projects utilising existing technologies.

A major challenge of such analysis is that sometimes the costs or benefits of technologies do not occur for a long time.

This challenge of inter-temporal comparison is exacerbated by the uncertainty inherent in the development of new technologies.

Problems that arise in the evaluation of technologies can be mitigated by making analyses transparent, ensuring there is disinterested oversight, evaluating relative to a broad reference class, allowing citizen participation, and being alert to the manipulation of analyses to achieve a result desired from self-interest.

Many countries have independent agencies to aid in the assessment of technologies to provide independent advice to citizens, governments and businesses. The general experience is that these agencies are valuable, but only when they are sufficiently connected.

When uncertainty is too great for evaluation, it can be reduced by conducting technological projects or trials.

The previous chapters have shown how technology changes, what its impacts are, what it means to people, and how it can be predicted. In order to act on such knowledge, for example to invest in a particular technology or technological artefact (or more generally to *intervene,* see Chapter 7), one needs to assess the value of a technology in a given context. Perhaps the most important factor affecting the adoption of technologies is their cost. Evaluation substantially influences technological change because technologies need investment if they are to be developed and commercialised. Investors of all kinds, from governments to firms and businesses, industries, purchasers, voters and other users evaluate in order to understand and anticipate the impacts of technology before deciding whether to invest or how to do so[72,745,889,950,1088]. The types of investments needed to create and diffuse technology include investments in time (by creators, potential purchasers and users of technology), creative and intellectual investment, and financial investment, none of which will occur without some evaluation.

The evaluation of a technology is not simple – the impacts of a technology are not intrinsic to the technology, and thus any evaluation needs to consider time, space and context (Chapter 4). Evaluating technologies is complex and fraught with uncertainty. There can be multiple causes of a particular event and intangibles are not readily quantifiable [1011] (Chapter 4). For example, evaluating the overall costs and benefits of a new medical technology is ‘more complex than the clinical evaluation of the technology’ [262]. The challenges of evaluating the economic consequences of new technologies designed for medical problems, such as achieving transparency, providing stakeholder representation, and the difficulty of determining indirect costs and benefits, apply to evaluating any technology [987 pages xii-xv]. Determining the cost of a technology is complex, contested, and dependent upon where the boundaries are drawn (for example, is the cost to future generations properly accounted for?). The way in which a technology is evaluated will affect investment in it, and its subsequent adoption by users or industry, people’s attitudes towards it, and ultimately its long-term impact.

In considering the evaluation of technologies it is convenient to distinguish three stages of technology development (noting that the boundaries between them can be blurred). In the first stage, technologies are still being developed. This is the R&D stage. In the second stage, the technology is 'new' and commercially available for use. In the third ('mature') stage, typically technology is several decades old. The future costs and benefits of the R&D stage are nearly impossible to evaluate in any precise fashion (Section 7.9.3). Mature technology, is more amenable to analysis, and there are some well-honed techniques that allow its evaluation. This chapter presents how to learn from the experience of investments in mature technologies in the form of large technological projects, since they have been studied in much detail. Specifically, the chapter discusses how such evaluations are done, what their problems are, and how those problems can be addressed with a view to translate these lessons to new technologies that are available for adoption by industry now. The problems that arise in evaluating new technologies are similar to those that arise in evaluating mature technologies. These difficulties will be examined through several lenses:

- Lessons from the evaluation of technological *projects* (typically utilising existing technologies) and methods that can reduce common assumptions and errors within technology evaluation such as optimism bias (Section 6.4.2).
- The value of conducting any evaluation in a broad context (Section 6.4.2).
- The challenge of intangibles, and the importance of *who* does an evaluation and the challenge of vested interests (Sections 6.4.3, 6.5).
- How to deal with the problem of inter-temporal choice, since new technologies typically take a long time to be adopted and have the effects realised. One needs to be able to compare costs now with benefits far in the future. (Section 6.4.4).
- The uncertainty of costs and benefits, which translate into risk for the investor, and methods of dealing with this risk (Section 6.4.4).

In order to improve evaluation of any technology, historical or emerging [66], societies should acknowledge, explore, discuss, and even challenge the ways in which people evaluate technology. Some technology evaluation methods, such as cost-benefit analysis, are better than others. Increased transparency of technological evaluation will aid rational discussion and implementation of public policy by promoting open access to analysis for critique and improvement. This chapter aims to make the complexity of evaluating technology manageable and examines how governments[47] can evaluate technologies.

6.1 What is a technology evaluation?

Investors in technology generally estimate and compare the costs and benefits of various technologies as well as their capacity to adapt to future impacts of technology (e.g. to avoid liability or exploit benefits), see Box 18.

What do users want from a technological evaluation?

1. The ability to estimate and compare the costs and benefits

A cost-benefit analysis for flood mitigation by a government, for example, would have to weigh the costs and benefits of implementing various technological projects.

2. The ability to foresee (where possible) beneficial or detrimental impacts/consequences

[47] Given the target audience of this report, the focus on government is natural. But it is essential to realise that there are other important actors, businesses evaluate technologies whenever they make an investment decision, and governments evaluate on behalf of the people they serve. Also, there are many ways in which citizens can participate in technology evaluation [258,920,950,1088,1092,1103].

Those who assess the consequences of building a dam, for example, would need to consider various options for siting a dam, building levees, diverting rivers, or other engineering solutions. Each of these options would incur social and financial costs (e.g. relocating existing communities) and be accompanied by direct advantages, disadvantages and externalities.

3. The flexibility to adapt and respond appropriately to unforeseeable impacts, whether desirable or undesirable

If an infrastructure option is chosen, an active management program incorporating ongoing monitoring, measurement and evaluation would be required in case of failure, and to allow continued measurement of the cost-effectiveness of the intervention.

4. The ability to understand impacts prospectively or retrospectively to avoid liability or benefit from desirable outcomes

For example, the Wivenhoe Dam was built in the 1970s in part as a flood mitigation exercise in response to catastrophic flooding of the Brisbane River in 1974. After its construction, the Brisbane metropolitan area did not experience flooding as severe as the 1974 floods in January 2011 [150]. During this 37 year period, the purpose of the dam changed from mitigating against floods to use as a reservoir during periods of drought. Severe rainfall in January 2011 led to the flooding of the dam and surrounding areas. Law firm, Maurice Blackburn, filed an action in 2014 on behalf of 4000 residents of Queensland against the Queensland Government and the dam operators (for over $2 billion in damages). Because there was a direct intervention to build Wivenhoe with public money, having provided the flood mitigation infrastructure, and changing the use of the dam from flood litigation to drought mitigation, the government is potentially liable for its perceived contribution to catastrophic flooding. The apparent failure of government and the operator may have contributed to community anger against flood damage even against the backdrop of over 35 years of effective flood amelioration [1042,1130].

Box 18: What do users want from technology evaluation?

There are many formal processes available to evaluate technology and there is a significant predictive element to these evaluations (Chapter 3). Much evaluation of technology is more accurately an evaluation of a technological project – the costs and benefits of a particular use of various technologies. For example, evaluating whether to build a particular power station at a given location, as opposed to an evaluation of the various technologies that may be used to produce power. Regardless of whether one is attempting to evaluate a technology or a technological project, it is helpful to understand the factors that affect such evaluations, and how the evaluations can be improved.

One cannot evaluate a technology isolated from its social context; the impacts of a technology are context dependent (Section 4.1). It is consequently of little value to attempt an *intrinsic* evaluation of a technology. The interconnected nature of technology and society affects how technologies are shaped and evaluated (Chapter 2). The use and adoption of technology is socially mediated and results from organisational, managerial, collective and individual practices and decisions. All of these factors complicate evaluation. Technology evaluation is multifaceted, widely used, but perhaps not well understood. This chapter examines evaluation in the light of some of the key aspects of technology established in the preceding chapters:

- Technology never functions in isolation because technology and society are interdependent.
- The economic performance of any technology or product will generally be affected by the availability and performance of component or complementary technologies or products, as well as their uses (individual and collective)[48].

[48] For example, reductions in transistor size with their accompanying developments in computers, compact digital cameras, mobile telephone technology, and improvements in wireless technologies

- Because the uses of a particular technology can rarely (if ever) be disentangled from the uses of other complementary, contemporary, or otherwise related technologies, investigating a technology in isolation imposes significant limitations on the evaluation of that technology [321,907].
- Policymakers, researchers, owners of businesses, representatives of different industries, funders, and the general public see technology differently and have different concerns (though these categories can overlap). These different perspectives and priorities affect the way an agent will evaluate the impacts of technology.
- Small technological changes have a cumulative productivity impact, which over time can be very large in terms of their effect on cost reduction, cumulatively larger than the impacts of major technical changes. There are several reasons why it is difficult to perceive these changes: 'the small size of individual improvements' (as in the case of the steam engine), 'a frequent preoccupation with what is technologically spectacular rather than economically significant' (for example the hovercraft), and 'the inevitable, related difficulty that an outsider has in attempting to appreciate the significance of alterations within highly complex and elaborately differentiated technologies, especially when these alterations are, individually, not very large' (e.g. mobile phones, which under their shiny surfaces hide enormous complexity and interdependence) [907].
- In an advanced industrial economy, technology changes are often hard to perceive. This gradual change can happen by means of 'a flow of improvements in materials handling', organisational changes (e.g. the construction industry); 'redesigning production techniques for greater convenience; and reducing maintenance and repair costs (as in modular machinery design)' which can prolong the life of capital goods (e.g. substituting old materials for new ones, like rust-resistant material) [907 , pp. 64-65, p. 67]; and not in 'great feats of creative genius, startling inventions or revolutionary ideas', [513 p. 64].
- Regarding the impacts of any particular technology, major productivity improvements typically 'continue to come long after the initial innovation as the product goes through innumerable minor modifications and alternations in design to meet the needs of specialized users' [907 p. 62].
- The effects of technology diffusion span industries and industry sectors.
- Uses of technology change over time, thus to evaluate one needs to predict potential future uses of technology which is fraught with uncertainty (Chapter 3). There are many ways to deal with uncertainty when evaluating, such as sensitivity analysis, scenario analysis, or raising the discount rate, but the limitations of each methods must be understood (Section 6.4.4).
- Cognitive biases play a major role when evaluating and making decisions (Section 5.2.4). The cognitive biases prevalent in technology analysis are similar to those in intelligence analysis [487]:
    - Vividness – information one perceives directly has greater impact; case histories and anecdotes are more vivid than aggregated statistics – one's direct experience with a technology failure will have greater weight than statistics that shows it to be reliable.
    - Not being aware of what one does not know ('out of sight, out of mind') – failure modes one cannot conceive of are ignored or heavily discounted.
    - Oversensitivity to consistency – because of technological interdependence, consistency of impact is rare.

---

allowed Apple and Android to design a better smartphone. In addition, communities of use had arisen which treated mobile telephones and personal organisers like the Blackberry as mobile offices. The emergent socio-technological systems [653 pp. 965-988: pp. 567-568] in which smartphones appeared continue to evolve as commuter and office, recreation, commerce, information, and communication practices change. These are influenced by the evolving practices of smartphone use.

    - Persistence of impressions based on discredited evidence – if early versions of a technology had severe defects, even after these are fixed, the perception can remain negative. Since most new technologies do have flaws when first introduced, this can be important.
    - Bias in favour of causal explanation (when dealing with phenomena that are truly random, spurious causation is imputed).
- Technology impacts are differential and those affected will behave strategically to improve personal gain, for example, by influencing the way the evaluation is done for their own benefit.
- Any technology evaluation needs to consider future states of the world because technological change takes time. Thus any technology evaluation must grapple with the uncertainty of the future.

6.2 Methods of technology evaluation – inside and outside views

Common methods of evaluation include cost-benefit analysis (generally prospective), lifecycle assessment (generally prospective, ongoing and retrospective) and reference class forecasting (generally prospective and retrospective). Table 3 describes some methods of technology evaluation including some associated strengths, weaknesses and viewpoints.

Evaluations or forecasts can be divided into two distinct types, those with an 'inside view' and those with an 'outside view' [273]. Forecasting from an inside view focuses tightly on the project at hand – the objective, the resources brought to it by the experts, obstacles to completion, customising scenarios of progress and extrapolating trends into the future. Resulting inside forecasts tend to be highly optimistic [370,631]. On the other hand, forecasting with an outside view of the project means the evaluator avoids getting trapped by the details of the project under assessment, and to learn from the experience of other related projects and technologies. If 100 similar projects went well over budget, it is likely the current project will too.

When forecasting based on inside and outside views is applied by equivalently experienced assessors, the outside view is more likely to produce a realistic estimate. This is because it mitigates cognitive and political biases, such as optimism bias and strategic misrepresentation [426]. 'The outside view is more likely to produce accurate forecasts and much less likely to deliver highly unrealistic ones' [370].

Type of evaluation	**Stage** **View**	**Description**	**Strengths**	**Weaknesses**
Cost-benefit analysis	P In	A systematic process for calculating and comparing benefits and costs of a product, process, project, decision or policy	Allows standardised measures (dollar cost) Different projects, design and implementation options can be compared for a given project; Sensitivity analysis and appropriate discount rates can allow for the risks associated with uncertainties Making cost–benefit analyses public (with clearly documented assumptions), improves the transparency of decision making	Externalities often unaccounted for Biases and assumptions of assessors Cost and demand forecasting are subject to strategic misrepresentation Lack of consensus

Type of evaluation	Stage View	Description	Strengths	Weaknesses
Reference class forecasts	R, P Out	A method to examine the experiences of a similar class of projects. This method forms a rough distribution of outcomes for a reference class and then positions the current project in the distribution.	Can assess more holistically than analysis of a single technology. Uses retrospective data to improve forecast. Data on more projects can help mitigate the problem of attribution of impacts. Outside view mitigates certain biases	Only as good as the data Need to choose an appropriate reference class, which brings in category error
Life-cycle assessment	R, O, P In or Out	A method of analysing the environmental impacts of a process, product or activity along its life cycle from 'the cradle to the grave'.[49]	Includes externalities Potentially more relevant and accurate because it considers whole of life	Results obtained can be difficult to extrapolate to other classes of problem Limited availability of data Collecting data is time-consuming and costly
Appraisal by business or industry leaders	P In	A formal or informal survey of relevant business and industry leaders, or a response to approaches by them	There is likely to be expertise vested in long-standing industries Understanding of some important context May receive a quicker answer than a systematic assessment	Vested interest Experience may be limited to a small number of options Psychology of previous investment or sunk cost [591] Appeals to convention/group-think Error or dishonesty Appeal to authority
Appraisal by experts	P In	A formal or informal survey of scientific or technical experts in a relevant field	Informed by relevant technical or scientific expertise and experience May receive a quicker answer than a systematic assessment would Understanding of some important context	Biases and assumptions Error or dishonesty Group-think Appeal to authority, which is a deductive fallacy Expertise may be limited, so response may not weight options from outside area of authority appropriately
	P			

[49] http://www.csiro.au/Organisation-Structure/Flagships/Sustainable-Agriculture-Flagship/Life-cycle-assessment.aspx

Type of evaluation	Stage View	Description	Strengths	Weaknesses
Popular opinion	Out	Surveys, opinion polls, consultation periods which solicit or respond to the opinions of the general public	Democratic: if a project requires public funding, then it seems reasonable that public opinions would be canvassed May receive a wide array of views informed by diverse experience and expertise	Unsystematic Lack required understanding of economic, social, technical or scientific context NIMBYism *Argumentum ad populum* (appeal to the masses); Bandwagon effect Biases and assumptions uninformed by expertise Public opinion may be overly subject to manipulation Psychology of previous investment or sunk cost [591]

Table 3: Some methods of technology evaluation [R = Retrospective, O = Ongoing, P = Prospective; In = Inside view; Out = Outside view].

6.3 Cost-benefit analysis

The best starting point in technology evaluation is conducting a cost-benefit analysis: predicting the future costs and benefits of some action, and comparing them to each other. It is an old idea: Benjamin Franklin advised a friend in 1772 to compile the relevant pros and cons of a problem as 'the weight of reasons cannot be taken with the precision of algebraic quantities … I think I can judge better' by bringing together all the considerations at one time [289]. Legislation that required the US Army Corps of Engineers to prospectively analyse the costs and benefits of a project (the 1936 *US Flood Control Act)*, was responsible for wider use of cost-benefit analysis (Chapter 7). Nowadays, cost-benefit analysis is largely taken for granted as the way to approach the evaluation of reasonably predictable complex action, such as the choice to adopt a particular commercially available technology. The cost-benefit analysis of new technologies can learn from some of the problems encountered in cost-benefit analyses of mature technologies. Large 'infrastructure projects' are the most widely studied technology evaluations. The remainder of this section focuses on what has been learned in performing evaluations of such technology projects and how this can be applied to new technologies.

Cost-benefit analysis attempts to measure the costs and benefits (and the associated consequences) of a project or technology so they can be traded off against each other [203]. Consequences can include effects on users or participants; effects on non-users or non-participants; externalities [1131]; option value (willingness to pay/valuation of risk factors) [1132] or other social or environmental benefits. In order to trade-off the costs against the benefits, they are typically all reduced to a common currency, usually monetary. Future uncertainty about costs and benefits are handled by discounting to net present value (Section 6.4.4). Differential impacts can be handled by separately accounting across the groups who are affected differently, rather than just looking at effects in aggregate.

The Australian Government stated in 2014 that public-works projects valued at '$100m or more in commonwealth funding will be required to provide a proposal to Infrastructure Australia that includes a cost-benefit analysis' [486]. There is no rationale for setting the threshold so high. The Australian Government's own cost-benefit analysis guidelines state that the level of analysis (and hence the *cost* of analysis) should be in proportion to the cost of the project. Furthermore, the benefits of obtaining and analysing additional information should always exceed the costs of doing so, so there is no need for a single (high) threshold [203]. Any choice to adopt or utilise technology will have costs and benefits.

Although there are some challenges and concerns with the practice of cost-benefit analysis none of them are sufficient to argue against evaluating technology through cost-benefit analysis [379]. The practice of cost-benefit analysis can be improved by improving the data available to reduce uncertainty in estimating costs and benefits, increasing evaluation transparency, reducing inherent optimism bias, evaluating intangibles and externalities and learning from previous analyses. Determining the extent to which cost-benefit analysis is currently used is difficult:

> Ascertaining the extent to which cost-benefit analysis is used by Australian governments is difficult; not least because such analyses are rarely published even if – or particularly if – they are used in the political decision-making process. One example of a well written, published report is that of the Auditor General of the Australian Capital Territory (2002), on the V8 Super Car races that examined the claimed economic benefits of the event [289].

Some high-profile examples of cost-benefit analysis are deficient. For example the analysis of the previous plan for the national broadband network has many critical numbers blocked out, making it impossible to validate the analysis [747].

Cost-benefit analysis (CBA) has been empirically demonstrated to be of significant economic value. Using cost-benefit analysis to inform decisions at a national level provides compelling evidence that it is worthwhile, as it improves government expenditure and investment capabilities. The budgetary impacts of the cost-benefit analyses conducted by the Netherlands Central Planning Bureau (a government agency) over a ten year period were studied [127]. For major infrastructure projects (more than €0.5B), a negative CBA verdict by the Bureau resulted in project delay or cancellation. The total costs and benefits of the cancelled projects was about €30B and €20B, respectively over that period. Therefore, the cost-benefit analyses by the Bureau led to a net €10B national surplus, [127] (page 33.)

It seems clear that cost-benefit analysis should be used to evaluate the use of technology and identify choices that increase welfare. However, merely mandating the use of cost-benefit analysis is insufficient guidance, because there is no single way a cost-benefit analysis can be done. For example, different costs can be determined according to whether the costs are conceived of as willingness to pay, or willingness to accept a negative outcome [203 page 32]. There are many ways one can argue for a particular choice of discount rate - different ways to account for risk (for example just amplifying the discount rate, or performing a more subtle risk analysis by perhaps performing sensitivity calculations), and an infinite variety of ways one can trade-off distributional effects (differential impacts amongst subgroups). Finally, traditional cost-benefit analyses do not adequately address subjective wellbeing [390] or environmental effects [73,310,820]. The more diffuse and long-term the effect, the easier it is to ignore as being too difficult to incorporate into a quantitative analysis. Disciplines such as life-cycle assessment [231] or 'genuine progress indicator' [467], social return on investment analysis [960], and the various methods for valuing intangibles [194,877] are all attempts to address these problems (see Section 6.4.3). These difficulties should not be ignored

Other issues that arise while using cost-benefit analysis for technology evaluation include:

- the omission of things that did not occur to the analysts at the time – this is the same challenge one has more generally in technological prediction (one cannot incorporate what one cannot imagine)
- the failure to consider unanticipated changes in the world in which the technology functions
- overconfidence in the accuracy of current scientific and technological knowledge
- failure to recognise the behaviour of a system as a whole
- common mode failures – for example, failure of taken-for-granted infrastructure such as reticulated electricity supply causes cascades of failures.

Technologies have flaws and sometimes fail, especially when first introduced. Technologists learn from these flaws and failures in order to improve the technology (Section 7.5). Likewise technology evaluation methods such as cost-benefit analysis have flaws, many of which are not widely recognised[50]. By identifying these, one can learn from them and avoid them in the future. The sections below cover the key failings and challenges in performing technology evaluation in order to learn how to perform such evaluations better.

6.4 Key failings, challenges and solutions to technology evaluation

The key challenges and solutions that the report considers are[51]:

- Vested interests and transparency (Section 6.4.1)
- Biases and assumptions (Section 6.4.2)
- Costing intangibles and externalities (Section 6.4.3)
- Comparing costs and benefits over time (Section 6.4.4)
- Learning from previous analyses (Section 6.4.5)

6.4.1 Vested interests and transparency

Cost-benefit analysis is widely used in technological evaluation. In theory, one assesses the costs and benefits, and then makes a decision. In practice, cost-benefit analysis is sometimes used to rationalise a decision already made for other reasons. A review of two Australian government departments highlighted this:

> Research found that the effectiveness of cost-benefit analysis in assisting public decision making is in a paradoxical situation. Conceptually, as agreed by public managers, cost-benefit analysis is a useful tool in assisting public decision making. However, in practice, by looking at two different departments, this study shows that cost-benefit analysis as a decision making tool has been used in pragmatic way to support their decision rather than as a 'rational' decision making tool. This happens and potentially undermines the creation of public value because of a lack of transparency in the use of cost-benefit analysis [1015].

The large differences often seen between *ex ante* and *ex post* estimates of costs and benefits for major infrastructure projects internationally show that 'it is not the best projects that get implemented, but the projects that look best on paper'. These are the projects with the largest cost underestimates and benefit overestimates [372,858,859].

There are analogous findings in the commercial world. When commercial firms are evaluating technology choices, 'intuition, symbols, rituals, and ceremony all [figure] prominently in the decision process' [1048]. Firms evaluate and then decide not only by considering the technology, but by also taking account of legitimacy and institutional norms – as one CIO commented 'when making IT spending decision, the Chief Executive Officer (CEO) just came up

[50] The basis of this assertion is the absence of any discussion of these factors in the Australian government's handbook on CBA [203,273] or in a recent edition of a standard text on cost-benefit analysis [696]. One exception, is the recognition by the UK government's 'Green Book' on evaluation and appraisal in central government of optimism bias as a major factor in CBA. In the words of the UK's chief economist Joe Grice, 'the new Green Book includes, for the first time, an explicit adjustment procedure to redress the systematic optimism ('optimism bias') that historically has afflicted the appraisal process'. He goes on to say 'There is greater emphasis on assessing the differential impacts of proposals on the various groups in our society, where these are likely to be significant' [493 page v].

[51] Other proposed improvements to the practice of cost-benefit analysis more generally, are not examined here see 'Proposed solutions for managing problems that result from the insolvable CBA limitations' [726] table 5.1, page 111.

with a consultant's average IT-to-revenue ratio for our industry, and then asked us to match it' [874].

Not all commercial[52] technology assessment is driven by such informal factors; some studies show how firms can grapple with the uncertainties intrinsic to technology selection, and crucially, how the adoption of formal and comparative measures can make decisions in a more rational manner [840]. The real tension arises when there is a high level of uncertainty about whether the technology will work as advertised. The risk to project failure is high, and many of the returns are intangible. It is then that executives resort to gut feeling (often euphemised as 'strategic insight') [676]. Unless one recognises the limitations of traditional rational analysis, one can hardly improve the situation. There are different approaches more suited to such uncertain environments, and these are presented in Chapter 7. The key point is how technology is evaluated *in practice*[53]. None of the criticisms of evaluation methods here or below implies that evaluation should not be done. As has been argued in the case of IT projects, and likely holds for technology projects in general:

> [T]he worst "solution" is to avoid evaluation. It is a fact of life that in many cases IT management tries to *manage* the risks associated with the project but also tries to *blur* the exact nature of the business benefits to be expected from the project and the exact magnitude of the uncertainty surrounding the project. A *qualitative* instead of quantitative *business case* is developed in order to avoid being committed to a set of very precise (but in all likelihood very difficult to achieve) targets. Due to the complexity of the determination of costs and benefits and the difficulty to predict the future success of new technology or new business models and the competitive reaction, top management is asked to commit to those strategic projects as an act of faith [676].

A cost-benefit analysis also considers the cost to whom. Cost-benefit analysis can arrive at very different answers depending upon who is bearing the cost, and is particularly distorting when a moral hazard exists. One suggestion for avoiding moral hazard problems in the evaluation of technology investments is to more fairly apportion the risk[54]. For example, the decision to invest

---

[52] It is not just in the commercial world that symbolic factors can distort evaluation. 'Symbolic' evaluations occur more generally quite often – for example 'fibre to the home' is symbolic of the 21st century information age (optical fibre is 'modern'; copper cable is old-fashioned); high speed rail is modern and desirable; medium speed rail is 19th century and to be shunned; electrical refrigerators (with their characteristic hum) were in fact marketed in this symbolic manner – the hum (which gas refrigerators did not have) was equated with being modern and therefore desirable [220].

[53] When this has been done, the results are similar to the state of affairs of cost-benefit analysis in government departments referred to above:

> We found that technologists did not present factual analysis of various alternatives to managers who then made judgment-based decision. Rather, the norm was for executives to make a judgment-based decision that analysts then justified and rationalized, or for decisions to be revisited until a desirable outcome was produced [1048].

[54] Flyvbjerg, has argued as follows[370]:

> The decision to go ahead with a major infrastructure project should, where at all possible, be made contingent on the willingness of private financiers to participate without a sovereign guarantee for at least one-third of the total capital needs. This should be required whether projects pass the market test or not—that is, whether projects are subsidized or not or provided for social justice reasons or not. Private lenders, shareholders, and stock-market analysts would produce their own forecasts or conduct due diligence for existing ones. If they were wrong about the forecasts, they and their organizations would be hurt. The result would be added pressure to produce realistic forecasts and reduced risk to the taxpayer. Forecasters and their organizations must share financial responsibility for covering cost overruns and benefit shortfalls resulting from misrepresentation and bias in forecasting…. The participation of risk capital would not mean that government reduces control of major infrastructure projects. *On the contrary, it means that government can more effectively play the role it should be playing, namely as the ordinary citizen's guarantor for ensuring concerns about safety, environment, risk, and a proper use of public funds* (italics added).

in electrical distribution infrastructure suffers from this problem[55], even though there was an independent regulator scrutinising the vetting the analysis by the proponents.

Other simple ways to ensure that those with vested interests are not given the task of conducting the analysis is to promote greater transparency[56]. It is much harder to hide assumptions that are driven by vested interests if the full analysis is available for all to see and critique [491,608,858]. It is not the general principle that is the problem; it is regularly and effectively implementing it in practice:

> However widespread the appeal of principles of openness and transparency in government, ideologies and principles in themselves are only abstractions. They must acquire traction in daily experience to breathe and endure [580 p54].

Leo Dobes, writing for the Australian Government's Office of Best Practice Regulation, suggests:

> A library of cost-benefit studies commissioned by all state and Commonwealth governments would provide a very useful resource for agencies. More importantly, a library would help increase transparency. Ideally, the 'library' should be fully open to the public, although particularly sensitive studies could be quarantined for internal government use only [289 p17].

This could be extended to all technology analyses done by or on behalf of government. Other aspects of the scientific method, such as facilitating criticism through open publication can improve the analysis and adoption of technologies (Section 7.6.4). In technology evaluation, there are tensions between the goals of net social benefit and personal gain [781]. Transparency and openness can help reduce this tension.

6.4.2 Biases and assumptions

Biases and assumptions affect decision-making, the way risk is judged, and perceptions of benefits and costs. They can be both conscious and subconscious, and are as much a part of cost-benefit analysis, as of everyday decision making (Section 5.2.4).

Optimism bias is perhaps the single largest cause of error in cost-benefit analyses of technological projects. Costs are routinely underestimated and benefits (such as revenues) are overestimated. These effects are so pervasive that they can be empirically estimated and have been mandated as 'optimism bias uplift factors' in any cost benefit analysis of large-scale infrastructure projects in the United Kingdom [493]. This section outlines the evidence for the pervasiveness and scale of optimism bias, and presents ways in which the bias can be mitigated.

---

[55] This is done on the basis of projections of future demand. Since distributors can pass on their costs (approximately half of the cost of electricity in Australia is due to the transmission and distribution costs) there is little incentive to err on the side of less investment. The consequence, investment of $45B in transmission capacity, is likely not to be needed because of the rapid rise of distributed photovoltaic power generation [489]. This illustrates the danger of allowing vested interests to do the initial cost-benefit analyses. Ironically, the extra infrastructure has driven the cost of electricity even higher and made distributed solar power more attractive, so that there is even less demand for the centralised electricity grid. As home energy storage prices drop, this effect will be even greater, leaving Australia with a huge bill for superfluous infrastructure.

[56] A government report describing the evaluation of a rail link from Brisbane to Melbourne illustrates the complexity of government evaluations of a technological project. Using the technology infrastructure company (i.e. the Australian Transport & Energy Corridor) to provide the initial numbers to conduct the cost-benefit analysis assessment was problematic. Because the company had a vested interest in gaining government funding, the figures provided were likely to have assumptions and biases (conscious or sub-conscious) resulting in inflated benefits and minimised costs, in order to improve their chances of funding. As a consequence, the review of the cost-benefit analysis by the Bureau of Transport and Regional Economics was also grounded in the initial numbers (anchored from an optimistic viewpoint) provided by the technology company [273].

While the analysis and evidence is focused upon technological *projects*, the conclusions can be more widely applied. When evaluating any technology, look at a broader 'reference class' of different, but related, technologies. For example, when evaluating the dangers of new forms of energy production, compare them to the dangers of alternative methods using empirical evidence.

It has been shown that transport projects, sports stadiums, public buildings, power plants, dams, water projects, oil and gas extraction plants, information technology systems, aerospace projects and weapons systems follow a general pattern of cost underestimation and overrun [366]. The causes of inaccuracy in the forecasting of major infrastructure include [373]:

- Difficulty in quantifying, identifying, and including 'external' costs and benefits.
- Inherent risks that stem from long planning horizons and complex interfaces.
- Possible non-standard technology and design.
- Involvement of many parties – with conflicting interests – in the decision-making, planning and management. Often a certain project concept is locked in or captured at an early stage, leaving analysis of alternatives weak or absent.
- False accuracy. Statistical evidence shows that unplanned events are often unaccounted for, leaving budget and time contingencies lacking. Such evidence comparing cost-benefit analysis data for major infrastructure is possible because recent advances in ICT permit the accumulation and interpretation of large data sets.
- Significant change over the time of the project's scope or ambition (Figure 12) [858].

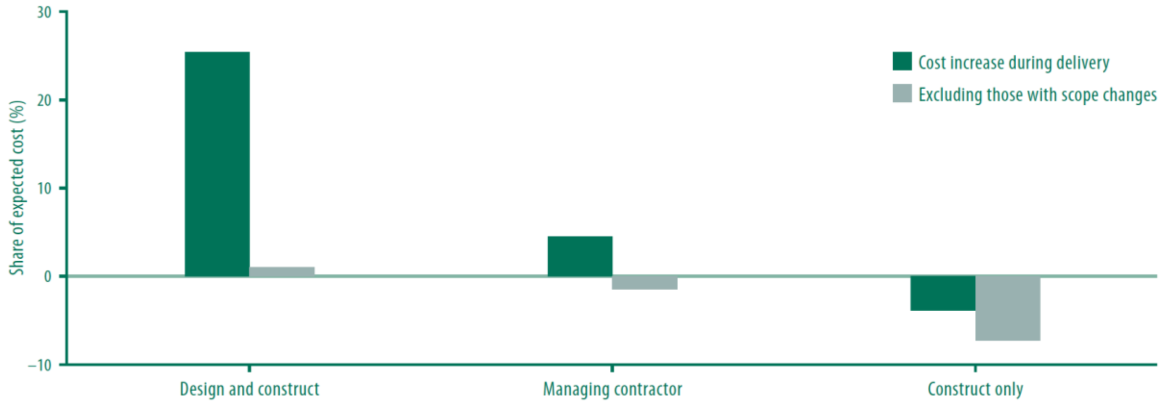


Figure 12 Cost overruns during infrastructure delivery mainly stem from government clients changing the scope of the project. Sourced from [858].

Consequently, inaccuracy regarding costs, benefits, and risks can occur throughout project development and decision-making.

Cost forecasting of major technology infrastructure

In general, infrastructure such as roads and railways is funded through the government. A study by Flyvbjerg reported cost overruns for major technology infrastructure at approximately 20–50%, and at times 100%, in real terms (Table 4). These figures are considered conservative, because cost overrun describes construction costs alone – financing costs, operating costs and maintenance costs were not included in the study[57] [370].

[57] The data are from the largest database of its kind. Cost overrun, also sometimes called 'cost increase' or 'cost escalation', is measured according to international convention as actual outturn costs minus estimated costs in percentage of estimated costs. Actual costs are defined as real accounted construction costs determined at the time of project completion. Estimated costs are defined as budgeted, or

Type of project	Number of cases	Avg. cost overrun (%)	Standard deviation
rail	58	44.7	38.4
bridges and tunnels	33	33.8	62.4
road	167	20.4	29.9

Table 4: Inaccuracy of transport project cost estimates by type of project, in constant prices [372]

The process of forecasting the likely demand for a project once the project is completed and available for use is called 'demand forecasting'. Demand forecasts can be inaccurate by 20–70% when compared with actual demand after project completion (Table 5).

Type of project	Number of cases	Avg. inaccuracy %	Standard deviation
Rail	25	-51.4	28.1
Road	183	9.5	44.3

Table 5: Inaccuracy in forecasts of rail passenger and road vehicle traffic [372][58]

In a sample of 25 cases, 84% per cent of rail passenger forecasts were inaccurate by more than ±20%. The same study found nine out of ten rail projects overestimated traffic demand. Inaccuracy in traffic forecasts was found in the 14 nations and 5 continents covered by the study. Half of the road traffic forecasts were wrong by more than ±20%. Demand forecasting inaccuracy was constant for the 30-year period covered by the study, and biases of a large magnitude formed the basis of cost-benefit analyses in a number of major infrastructure projects globally, highlighting the need to improve methods [370].

The accumulation of the following factors can lead to the underestimation of costs, overestimation of benefits and systematic underestimation of risk when evaluating technology [631]:

- Underestimation of uncertainty and overconfidence in projects going as planned:

  > Technical explanations account for cost overruns and benefit shortfalls in terms of imperfect forecasting techniques, inadequate data, honest mistakes, inherent problems in predicting the future, lack of experience on the part of forecasters, etc. This is the most common type of explanation of inaccuracy in forecasts [370].

- Cognitive biases and organisational pressures have been put forward as explanations for executive overoptimism leading to inaccurate cost-benefit analyses.
- Suppression of pessimism and a preference for optimism can limit an organisations ability to think critically.
- Political-economic reasons – project planners and promoters might deliberately and strategically overestimate benefits and underestimate costs. They do this in order to increase the likelihood that it is their projects, and not the competition's, that gain approval and funding.
- Competitor neglect is particularly destructive in efforts to enter new markets because the optimistic view is that there are none or very few competitors and the well forecasted project will succeed.

Some projects in Australia that were initially viewed by many as overly expensive, risky and misguided, have nevertheless achieved substantial public benefit and community support. The Sydney Opera House, the Snowy Mountains Scheme and C. Y. O'Connor's water supply scheme

---

forecasted, construction costs at the time of the decision to build. It is difficult, however, to find valid, reliable, and comparable data on these types of costs across large numbers of projects. For details on methodology of the study, see [374].

58 Following international convention, inaccuracy is measured as actual traffic minus estimated traffic in percentage of estimated traffic. Rail traffic is measured as number of passengers; road traffic as number of vehicles. The base year for estimated traffic is the year of decision to build. The forecasting year is the first full year of operations. Two statistical outliers are not included here. For details on methodology, see [372].

to the Western Australian goldfields, are some examples. Such 'visionary' projects, often do not work out well, as evidenced by examples such as the Ord River Irrigation Scheme [858]. Although the initial cost-benefit analysis of the Sydney Opera House was notably inaccurate [372], current analyses show its value exceeds its lifetime cost [265]. But for every successful iconic project, there are many failures.

Reference class forecasting

One can learn from the mistakes of the past. The method outlined below not only addresses optimism bias, but can also help mitigate strategic misrepresentation [369]. The idea is simple: 'Because cost overruns are so common, estimates can be corrected for optimism using a method to deal with optimism bias'[367]. This is done by correcting ('uplifting') the forecast costs by a factor derived from the average cost overruns of analogous projects. An example uplift curve is presented in Figure 13.

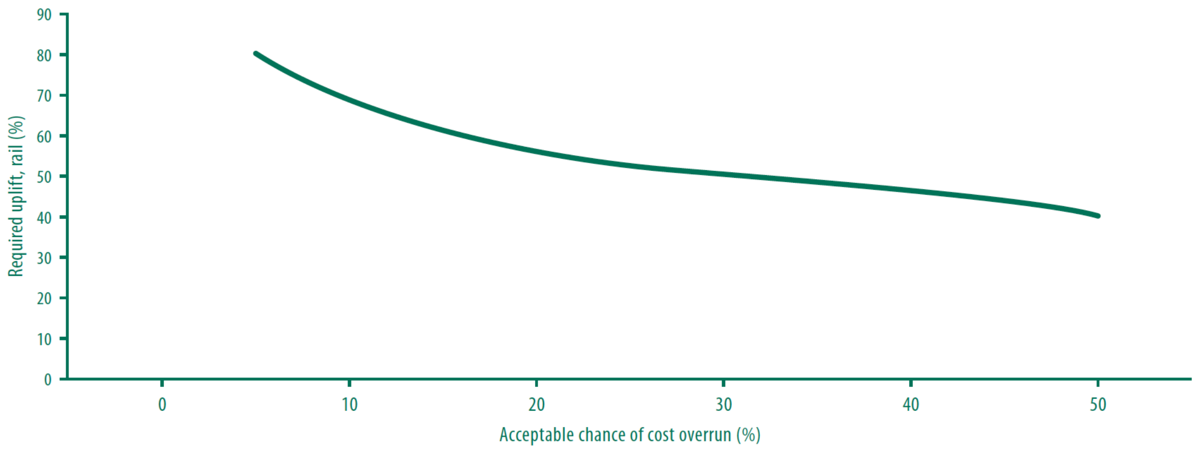


Figure 13 Required uplift as a function of the maximum acceptable level of risk for cost overrun. Sourced from [367].

The British Department of Transport and the American Planning Association have adopted reference class forecasting[59] methods with 'the strong recommendation that planners should never rely solely on conventional forecasting techniques when making (large scale) forecasts'[371]. They are mandated in the UK [493,494] and have been recommended for use in Australia by the Productivity Commission [858].

Reference-class forecasting has been corroborated as an effective tool based on the availability of reliable open information [426]; the method cannot work if the requisite information is not

[59] The method in summary is:

1. Select a reference class – Based on the outcome the project aims to achieve i.e. Introduce a new processing technology to increase productivity
2. Assess the distribution of outcomes – Document the outcomes of similar prior projects and arrange them as a distribution (median, extremes etc.)
3. Make an intuitive prediction or your project's position in the distribution
4. Assess the reliability of your prediction – Gauge the reliability of your prediction from Step 3. Estimate the correlation between the forecast and the actual outcome.
5. Correct the intuitive estimate – An aid in removing the likely optimistic bias in step 3 [370].

Reference class forecasting was first used in practice in 2004 to estimate capital costs of the proposed Edinburgh tram line 2 [368]. An initial cost estimate of £320m made by planners was adjusted for optimism bias and acceptable risk. This resulted in a new cost estimate of £400m, including contingencies to insure against cost overruns at the 80% level, i.e. with a 20% risk of overrun. Since the Edinburgh Tram, many other infrastructure projects have been subjected to reference class forecasting.

shared (Section 6.4.1). Evaluations or forecasts can be divided into two distinct forms, the inside view and the outside view.

Taking a broad perspective - the outside view

Reference class forecasting encourages taking an outside view. Research shows that when people are asked simple questions requiring them to take an outside view, their forecasts become significantly more accurate. The outside view is much more likely to produce a realistic estimate because it mitigates cognitive and political biases, such as optimism bias and strategic misrepresentation.

The comparative advantage of the outside view is most pronounced for projects that have never been attempted in a specific location before – such as building an urban rail system in a city for the first time, or launching a completely new product to the market. It is in the planning of such new efforts that the biases toward optimism and strategic misrepresentation are likely to be largest. A key challenge is to gain acceptance of the outside perspective:

> The inside view is embraced as a serious attempt to come to grips with the complexities of a unique challenge, while the outside view is rejected as relying on a crude analogy to superficially similar instances. Yet the fact remains: The outside view is more likely to produce accurate forecasts and much less likely to deliver highly unrealistic ones [370].

The outside view can also assist in the more general evaluation of technologies. As explained in Chapter 4, all new technologies have downsides, and comparing those costs within a broader frame can be instructive. For example, the major concern regarding nuclear power is its safety. This could be crudely quantified by looking at the number of deaths per unit of energy generated (Table 6). When such an analysis is done for the major sources of primary energy used in the world at present, the results are surprising[60]:

Energy source	Percentage of world's energy	Deaths per TWh[61]
coal – world average	26	161
coal (China)		278
coal (US)		15
oil	36	36
natural gas	21	4
biofuel/biomass/peat		12
solar (rooftop)	0.1	0.44
wind	1	0.15
hydro[62]	2.2	0.1
nuclear	5.9	0.04

Table 6: Number of deaths per TWh for different energy sources. Sourced from [1112].

This table illustrates how much safer nuclear power has been than coal, so far – a factor of 375 or 4025 depending on whether the US figures or the world averages are used. Merely by evaluating more broadly one can gain a better insight into the *relative* costs of different technology choices.

[60] Any such analysis can (and surely will) be contested, but the broad conclusions are on solid ground. Other evidence includes the US National Academies report [1038], the Australian Academy of Technological Sciences report [114], and others [562,988].
[61] TWh= TeraWatt-hour, a (large) unit of energy – 1 terawatt (10^{12} Watts) for one hour = 3.6×10^{15} Joules.
[62] If the Banqiao disaster is included these numbers are quite different. The Banqiao disaster was the simultaneous failure of multiple hydroelectric dams in China in 1975, which led to 171,000 deaths [1129].

6.4.3 Costing intangibles and externalities

Intangibles and externalities can be the major cost of adopting a technology in the long term. The valuation of intangibles (such as a corporation's human capital) and externalities (such as total environmental impact) is a well known problem[63]. Thus their evaluation can be as important as quantifying tangible costs and benefits (e.g. operational expenditure, capital outlays) and revenue forecasts during technology evaluation [970].

Intangibles that are generally not incorporated during technology evaluation include:

- Longer term environmental effects that are not readily reduced to an economic value [744,820].
- Opportunity costs [632].
- Spillover benefits of investment in early stage technology research and development [327].
- Reduction of future flexibility due to infrastructure decisions now[64].
- Path dependence effects, including lack of skills through lack of investment in appropriate training and education [27,296] pride, amenity impacts, potential 'branding' value (fundamental to iconic and cultural building projects) and business reputation.
- Factors such as ethics, knowledge, equity, civic pride, dignity and experience could also be described as qualitative benefits [1018].

Externalities and indirect costs and benefits generally not assessed when evaluating the production and use of technology include specific social implications and total environmental impact [744]. Indirect costs and benefits include values (e.g. research approach); use of all relevant resources, lifecycle effects of new infrastructure (e.g. water, land, concrete, steel etc.); production processes (e.g. extraction of raw material, fabrication, assembly and maintenance); equipment decommissioning/disposal (except nuclear technology which automatically creates higher costs for nuclear power cost-benefit analysis compared to other non-nuclear power energy sources such as fossil-fuels); environmental health impacts (air/groundwater pollution); and total human health impacts (e.g. toxic emissions of nitrous oxides, sulphur oxide) [23]. External costs have been described as social costs that are not paid for by the producer or the consumer of the technology [114].

While intangible and externality costs can be difficult to calculate, the inability to ascribe monetary value to social or environmental impacts should not cause exclusion from the decision-making process of cost benefit analyses [194,877]. Qualitative analysis (e.g. knowledge, equity, dignity) is as important as quantitative analysis in technology evaluation (see [890]). Best practice in technology evaluation explicitly turns the costs and benefits into numbers when possible.

Coal-fired power plants are a form of energy-producing technology for which direct and indirect costs of carbon pollution can be attributed. Generally, the utility industry's main measure for the cost of electricity produced by a generator is called the 'levelised cost of energy' (LCE). LCE is calculated from the cost of electricity generation at the point of connection to a load or electricity grid. It accounts for a system's expected lifetime costs (typically 20 years) to the producer, including construction, financing, fuel, maintenance, taxes, insurance and incentives,

[63] Regulation imposes risk assessments to evaluate environmental and human health impacts in defined settings with the aim of protecting public interest during the use of technology (i.e. chemical and pharmaceutical regulation). In addition, quantitative indirect costs have been established for travel (i.e. congestion, air pollution, greenhouse gas emission) and costs to property prices in the vicinity of a project which can be incorporated into a cost-benefit analysis.

[64] See [633]. Approximately a decade ago there were some 1.2 million phone services connected via pair-gain systems which was a blocker in the deployment of ADSL, [959], page 9.

which are then divided by the system's lifetime expected power output (kWh). All cost and benefit estimates are adjusted for inflation and discounted to account for the time-value of money and the risks involved [879]. LCE does not generally account for substantial capacity for emissions and waste burden formation from energy generation (e.g. upstream of energy end use by the consumer, extraction of raw energy at source, processing and conversion to electricity, and transmission and distribution)(see Figure 14) [744].

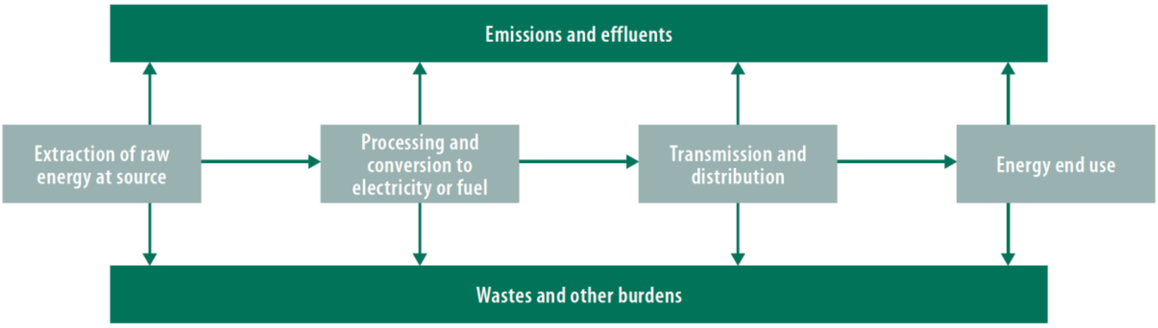


Figure 14 Life-cycle analysis for energy use. Sourced from [744].

The EU's ExternE project and the US National Academy of Science have each produced methods to cost externalities for power generation [339,744]. They highlight the large amount of uncertainty involved, but externality costing methods are globally considered as conservative [586]. Perhaps because of the residual uncertainty in assessing the externalities, such methods have generally not influenced policy. While it is impossible to remove all uncertainty, it is better to attempt to quantify the externalities when assessing technologies, rather than using the uncertainty as a reason to ignore them.

In the case of coal-fired energy generation, the cost of environmental and human health burden is based on the amount of power generation facility emissions such as particulate matter (PM_{10}), nitrous oxides (NO_x), sulphur dioxide (SO_2) and carbon dioxide (CO_2). Emissions are calculated using a 'willingness to pay' model that estimates the cost society could pay to avoid environmental and human health damage [876].

In Australia in 2009, with existing regulations the levelised cost of producing electricity from coal was \$40/MWh. However, the calculated external costs was \$39/MWh, resulting in a total 'cost' of \$79/MWh. Therefore consumers paid for half of the real cost of producing and using electricity generated from coal. The external costs are largely based on environmental and human health damage due to emissions such of CO_2, PM_{10}, NO_x and SO_2 [114]. It should be noted that the external costing is an average of a large number of coal-fired power plants and that newer coal plants have lower external costs because of pollutant-capturing technology.

Often the costs of a technology are not apparent at the time of adoption. The consequences of pollutant emissions from fossil fuel electricity generation were not known until many decades after the widespread adoption of this technology. Technological innovations over the last few decades have allowed the evaluation and modelling which link fossil fuel emissions to climate change [395].

Externalities and intangibles remain critically important and have a large impact, but are often neglected because their measurement is difficult and there is no single or simple process by which they can be incorporated into a technology evaluation. No simple recommendation is offered here other than they cannot be ignored. In a society that is heavily focused on economics and quantification [848,952], failing to price something, effectively means ignoring it. In some way a price needs to be attached. Pigouvian taxes[65] or trading schemes [409,744,783] are ways of achieving that (Table 7).

6.4.4 Comparing costs and benefits across time

The development and adoption of technology relies on the willingness of investors to invest which requires evaluation. A key challenge in the evaluation of technology is that its impacts can take a long time to occur [241], (Section 2.2). One needs to compare present costs with future benefits. This is often done by discounting the future benefits to present value so they can be compared to the present costs. Discount rates are also used as a means of factoring in the pervasive uncertainty and risk of future predictions. This section examines the various means for comparing costs and benefits of technologies across time, and how to deal with the uncertainty of future costs and benefits.

Technological developments are heavily path dependent[66], prone to lock-in and inherently uncertain. Technology progresses in an evolutionary manner in fits and starts (Section 2.3). These factors are a substantial challenge in assessing the cost of a technology because one may need to compare the cost of technology A (available now) with technology B (which becomes available in the future). The comparison of choices across time is called 'inter-temporal choice' by economists. It recognises the fundamental fact that:

> A good at a certain date and the same good at a later date are different economic objects, and the specification of the date at which it will be available is essential [253, p 29].

The most widely used means of comparing costs at different points in time is the Discounted Utility (DU) model introduced by Samuelson in 1937 [929], see also [629].

> Despite Samuelson's manifest reservations about the normative and descriptive validity of the formulation he had proposed, the DU Model was accepted instantly, not only as a valid normative standard for public policies (e.g., in cost-benefit analyses), but as a descriptively accurate representation of actual behavior. A central assumption of the DU model is that all of the disparate motives underlying intertemporal choice can be condensed into a single parameter – the discount rate [381, p 351].

The idea is simple: future utility is translated to present utility by discounting (for example by 5% per year). The discounted utility model is theoretically and practically attractive. Under conditions of certainty it has desirable consistency properties.

> Time consistency in a world of certainty means that what is optimal to do tomorrow, seen from today, is still optimal the next day [436, section 15.2].

But this comes at the price of being a questionable model for reality. People disagree on which discount rates to use, primarily because there are differences in opinion on the level of risk involved[67]. There is no single correct discount rate; the choice of discount rate depends upon

---

[65] Pigouvian taxes (such as a tax on carbon emissions) are imposed on 'bads' not 'goods', as a way or ascribing a real monetary cost to otherwise uncosted negative externalities.

> When energy use externalities are the only market failure, the evidence consistently shows that product taxes and related energy efficiency standards are extremely costly second best policies relative to the first best Pigouvian tax [18].

[66] There are many irreversible choices regarding new technologies, some less obvious than others. One can discount the cost of painting a wooden house – defer the painting for a year, and the net present cost can be reduced by the discount factor. But do this too often, the wood rots and it is not simply a matter of paint anymore – one needs a whole new house. Destroying research and development institutions (which take decades to build) that train people with advanced technological skills is not easily reversed in a few years time. Discount rate based analyses of such decision would be misleading.

[67] Table 1 of [381] illustrates an extraordinary range of discount rates.

many factors[68]. The outcomes of a technology evaluation, such as the calculated costs and benefits, are very sensitive to the discount rate chosen [381, see section 6]. Use of a quite modest discount rate can mean that even with a fairly modest discount rate the benefits that are more than 10 years away have very little influence on the cost-benefit analysis because they are worth little in present value terms.

The discount rate deals with the time value of money and reflects the assessed risk of a project. The single discount rate number is typically required to do double duty as a way of incorporating future uncertainty by increasing future discounting. The logic being that greater uncertainty of a future outcome should simply require its benefits to be discounted more. The Australian government cost-benefit handbook, however, recommends against only dealing with uncertainty by raising the discount rate, [203] (page 76.)

There is inconsistency regarding how the discount rate is adjusted during technology evaluation because of different perceptions of the degree of risk and uncertainty [381]. Merely raising the discount rate does not capture the richness of uncertainty models one needs for complex future technologies. There remains debate in economics about the best way in which to evaluate complex risks. It seems prudent to at least perform sensitivity analyses to understand the range of answers possible in the light of uncertain information [203].

Path dependence and lock-in are not captured by simple exponential discounting. Technological change exhibits a rich 'non-ergodic' behaviour, 'perturbations that perturb the system will not necessarily be "averaged away" with the passage of time' [245] – they can settle into states from which it is very hard to exit. A critically important example is what needs to be done *now* regarding carbon pollution. It can be argued that merely using discount factors does not adequately cope with the time-delays of technological change [453].

More sophisticated models of risk and time are available which eschew models whose only virtue is mathematical simplicity [436], and some (although not accepted by all economists) seem a much better fit for the evaluation of future technologies such as [409].

> The title of this valuable work...comes from a remark of J.M. Keynes: 'The social object of skilled investment should be to defeat the dark forces of time and ignorance which envelop our future.' The moral of this work, however, is that time and ignorance are not so much dark forces to be defeated as unavoidable aspects of the human condition that must be lived with.' - Kenneth Boulding, quoted in the front matter of [436].

The uncertainty of future costs and benefits is a major challenge for the evaluation of technologies. Even when faced with long-term uncertainty it may not be possible to sensibly assess technological impacts through a single number that a cost-benefit analysis is ultimately reduced to, it is possible to perform sensitivity analyses to deal with this. In the presence of extreme uncertainty, there are different approaches, such as on-going small scale experimentation and pilots that can be used, see Chapter 7.

6.4.5 Learn from previous analyses

Taking a historical view of how technologies were previously evaluated can give insight into improving technology evaluation. Much of the previous analysis of problems with methods of cost-benefit analysis relied upon being able to look at analyses that were done about the future, waiting for the future to arrive, and then looking at the gap between analysis and the present.

---

[68] The Australian Government handbook on cost benefit analysis [203, chapter 4] assumes that a single discount factor is used for inter temporal choice. Although alternatives to net present value are discussed (e.g. Internal Rate of Return, and payback period) all are predicted on simple single discount factors. Chapter (5) devoted to 'setting discount rates' does not even consider the possibility that a single number will not work.

This illustrates a simple but essential point: if one does not perform retrospective analyses, one will not learn. Retrospective technology evaluations – examining past technology evaluations in the light of what has actually come to pass – are illuminating in terms of what is foreseeable and what is not [192,843,1024]. It is difficult to attribute impacts to particular causes, therefore more detailed retrospective analysis could reveal which technologies are responsible for which impacts, and which historical interventions improved or degraded the outcomes. Retrospective and ongoing measurement and evaluation would improve technology evaluations.

Such retrospection further mitigate the various cognitive biases and strategic misrepresentations described above. They can lead to an understanding of how pervasive unanticipated consequences are [925]. Study of retrospective analyses [956][69] is valuable – it can help prevent people from making the same mistakes again. Detailed, open and honest retrospective analyses of major technological decisions would be valuable for future generations.

A review of technology evaluation methods used worldwide and the 'lessons learned' from these methods inform the following characteristics of good technology evaluation. These properties should be central to any useful and effective technology evaluation method to aid decision-making. Evaluations should:

- Be analytically rigorous, with in-depth and context-dependent information.
- Be transparent and available publicly.
- Include an oversight and pre-public review process (e.g. non-partisan).
- Be delivered quickly enough to aid decision-making.
- Be multidisciplinary and take a participatory approach [950].
- Honestly represent and recognise uncertainty where present.
- Address social consequences and social values.
- Recognise synergism and interdependency between technologies and between technology applications and collective uses.

Lessons for the evaluation of new technologies

Evaluating technologies that are new differs from evaluating technologies that are mature. At its newest, technology is being researched and developed, and the traditional approach of cost-benefit analysis is less applicable because of the extreme uncertainty of costs and benefits. The risk of initial failure is high in research and development, so to some extent the decision to invest and keep investing is necessarily based on a combination of experience, intuition, and faith. Nevertheless, a technology may be new to some users or industries, and not new to others. In order to evaluate new technologies, one can learn the following lessons from the evaluation of mature technologies:

- Cognitive biases play a large role in *any* evaluation. The techniques developed in technology project evaluation (comparing to a broader reference class) are readily translatable to the evaluation of new technologies: if 100 previous new software projects ran three times over budget, it is likely the one under consideration will also do so.
- Vested interests play a role in new technologies –proponents have an interest in inflating the perceived benefits to increase investment.
- New technologies take a long time to have an impact, and hence some form of inter-temporal analysis is essential. The uncertainty of new technologies is even greater than

[69] Examples include [192,1024] [1025] [604,843] [385]. Such retrospective analyses have lead to very surprising and controversial conclusions – see the analysis of the effect of bombing entire cities in WWII in [321], (pages 14-19].). Confer [646] and [1017].

for mature ones, so sophisticated means of incorporating that uncertainty are essential for the evaluation of any new technology.

- New technologies always have their own sets of intangibles, not least of which are unforeseen consequences. These need to be allowed for in the evaluation of new technologies.

When the evaluation of a new technology leads to a decision not to invest, alternatives include waiting until the technology further matures, or conducting further laboratory trials or experiments such as small-scale pilots or developing prototypes.

6.5 The role of independent technology evaluation and assessment agencies

Precisely because the assessment of new technologies is controversial they should be taken seriously, rather than using the controversy to argue that the issues can be ignored [889]. The presence of controversy in the evaluation of new technologies motivates a particular oversight role for government. Governments have conducted technology evaluations (more usually called 'assessments') in many guises[70]. Many governments and parliaments have created independent agencies to assist in this oversight. These include the Danish Board of Technology, UK Technology Strategy Board, Science and Technology Options Assessment, European Parliamentary Technology Assessment and (until 1995) the US Office of Technology Assessment [333,341,790,926,1069]. A number of discipline-specific technology assessment groups have formed recently with different levels of effectiveness (e.g. health technology assessment) [70,574].

Institutions for technology evaluation can be effective, particularly when they aim to do independent and transparent technology evaluation [226,260]. There is a key trade-off between independence, which might increase the risk of being ignored, and being tied closely to power, in which case there is a risk of being corrupted. There is a further risk that technology evaluation agencies tend to usurp what politicians view as their domain – the choice of grand projects.

Existing public structures perform technology evaluations in Australia. For example, the Therapeutic Goods Administration assesses human pharmaceuticals and new procedures (such as MRI when it was introduced), and the Department of the Environment requires an environmental impact statement if projects are deemed significant. Nevertheless Australia lags many countries in the use of technology evaluation to inform technology policy (on biotechnology policy, for example) [920]. The delay can be attributed in part to the poor standard of debate and analysis on technology evaluation. Unlike the large number of committees recommended in the Myer report [200], the present report does not recommend any particular structure or committees. Inspired by the analysis of Sclove [950], it does seem clear that Australia needs to:

- Recognise the importance of evaluation of new technologies. There are always choices that will be made one way or the other; making these choices as informed as possible is necessary.
- Recognise that the value of a new technology is extrinsic, and so one cannot simply make a single determination of the value of a given technology as its value may change over time.
- Have an ongoing capability to assess new technologies, using as broad a constituency as possible, to counter the interests of those heavily vested into current technologies; deal with the inability of any single expert to understand all the relevant factors; and gain a

[70] For a history of technology assessment in Australia see pages 776 and 777 of [722].

more complete evaluation of social consequences (e.g. democratic participatory technology assessment).

- Be prepared. Technology evaluations can take years to complete; this timeline can lead to in-depth consideration of many issues often long before these issues come to the general attention of legislators [332].
- Recognise that the problems of technology evaluation cannot be effectively solved by one off projects (like the present report). Apart from anything else, no single group will have the expertise to evaluate all technologies [597].
- Gain insight into technology synergisms and socio-technological dynamics. The interdependence of technologies implies that most social influences will arise from complex combinations of technologies, and thus assessment in isolation will be of limited value.
- Conduct independent and balanced technology evaluation. Recognise that any expert assessment will have its biases. This does not mean that expert views should not be used, simply that the evaluation should be transparent and critiqued. Appraisals could be shifted from promoters to more neutral ground, for instance the Department of Finance or Productivity Commission, in order to reduce risks of agency problems.
- Have a variety of groups initiate assessments (by contrast, the Productivity Commission which only investigates a topic when asked by the government).
- Understand the boundaries of technology and who is responsible for the evaluation.
- Acknowledge that technology assessment capability needs to be contextually embedded because the impacts of new technologies are contextual. Without deep knowledge of the context, one will err.
- Those involved in a technology evaluation should be as impartial as possible:
    - Allow for evidence-based evaluation
    - If those with strong self-interest conduct evaluations then the answers will be distorted in favour of the interested party.
- Be able to deal with systems. The interconnected nature of technologies means that evaluation and assessment regularly hits boundaries, especially jurisdictional ones so analyses need to be done in a manner that can readily cross traditional boundaries [403].
- Be able to deal with 'social technologies'. Technologies often overlap with the social sphere (such as new ways of organising work) and cannot be compartmentalised as technology in the narrow sense of machines. The view of regulation as a form of technology could make legislators feel they are being put out of a job by technologists: 'The concept of social technology flies in the face of the self- imposed customary and putative functions of legislators' [191].

6.6 The value of technology evaluation

Technology evaluation and assessment is central to the development and adoption of new technology. Since cost is a major determinant of technology adoption by individuals, businesses and governments, the way that technology is costed is critical.

Cost-benefit analysis is the best starting point for the evaluation of technologies since all technologies have both costs and benefits, and decisions on developing or adopting technologies depends upon their trade-off. Such analyses should be required when considering the adoption of any technology [203,289,858,859]. They will be more valuable if methodologies and assumptions used are transparent.

The value of a cost-benefit analysis depends crucially on who is doing it, who can see it, and what other agendas they are pursuing. Analysis could be shifted from promoters to more neutral ground, for instance with the Department of Finance or Productivity Commission, in order to reduce risks of agency problems [372,858,859]. At the very least there should be independent oversight of such analysis.

Self-interest of individuals, corporations or governments can mean that cost-benefit analyses are sometimes done backwards, starting from the desired outcome and manipulating the analysis to obtain the desired result, rather than working forward from the data.

There are differential impacts of technology – any one technology will affect people in different ways depending on the context. Evaluating the costs of technology depends significantly on the costs to *whom*. Calculating the benefits of technology faces the challenges of optimism bias and strategic misrepresentation. It is possible to mitigate against biases and assumptions during technology evaluation by using methods such as optimism bias uplift and reference class forecasting (Section 6.4.2).

The above issues can be dealt with by retrospective, ongoing and prospective evaluations should inform one another. This is only possible if data is available, reusable and sharable [306]. The availability of such data also allows improved evaluation-based decision-making and intervention. The credibility of assessment methods depends on transparency and on avoidance of vested interest. Transparency improves technology costing and analysis as it allows others to check the analysis, which increases robustness and replicability, and provides a greater degree of trust in technology choices, interventions, and decision-makers [858].

Since technological change takes time, the evaluation of new technologies needs to deal with the problem of inter-temporal choice (e.g. when to invest?). There is no single, simple way of taking the temporal element into account. Discount factors are one way of doing so, but the choice of discount rate remains problematic, and it can make a major difference to the conclusions, especially for long-run benefits and costs. Technological uncertainty cannot be captured adequately by reduction to a single number.

Technology evaluation in general, and cost-benefit analysis in particular, can be improved by adopting certain practices already widely used around the world:

- Do technology analysis with as much local expertise as possible.
- Recognise that due to technological interdependence, analyses will depend upon the evaluation of predecessor technologies. Open shared data facilitates this interdependent evaluation.
- The evaluation of intangible costs, although difficult, can and should be done. Intangible costs such as environmental effects can in the long run be the major cost of adopting a technology. They are as important as the more easily quantifiable and appropriable economic returns.
- Avoid manipulating analyses to get the answer a self-interested party desires. Make analyses and their supporting data as open as possible, and ensure there is are mechanisms to conduct evaluations on behalf of *all* citizens.
- Mitigate against optimism bias by calibrating analyses using optimism bias uplift factors as used in reference class forecasting.
- Assess technologies in a broader context – if a certain technology causes harm (e.g. deaths) put it into context by looking at the frequencies of other causes of death.
- Recognise the differential effects of technologies, and ensure that the disenfranchised and less powerful can contribute to technology evaluations through participatory means.

Ultimately there is only so much one can do in evaluating a new technology in the present. This is a problem for new technologies,

> because during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development; but by the time these consequences are apparent, control has become costly and slow [196] (quoted on page 2 of [981]).

Sometimes evaluation is not possible, or at least not sufficient for guiding future actions. Costs and benefits of technologies are uncertain and unpredictable. Consequently, one may need to wait for the technology to mature, or to conduct experiments such as small-scale pilots, learn from them, and adapt according to their outcome (Chapter 7). Such a constructive approach to decision-making that involves ongoing measurement and monitoring, adaptation and learning [945] is the focus of Chapter 7.

7 Intervention

Summary

The complexity of the evolution of new technology means that interventions need to be adaptive and devolved.

Interventions need to take an extrinsic approach because the impacts of technologies are not intrinsic.

Creativity and tinkering are essential skills for facilitating technological change.

Technologies progress by learning from failure. Designers of technological interventions can learn from technologists and scientists.

Explicit experimentation is the best strategy to deal with the inherent uncertainty of new technologies.

Interoperability can be facilitated by standards, gateway technologies and platform technologies.

It is better to design regulations that focus upon the effects of technology, rather than on the technology itself.

The economic returns to early stage technological R&D are hard to appropriate. Consequently continued government investment is needed.

Previous chapters have shown the complexity, unpredictability and manifold effects of new technologies. What might be done in response? How might one *intervene*? This chapter examines the forms of technological intervention available, the challenges of designing and evaluating interventions, and suggests how to make interventions more effective.

An *intervention* is any action designed to cause an outcome. With regard to new technologies, one may wish to encourage or discourage a particular technology through regulation, market mechanisms, investment or divestment, or skills development; introduce new controls on the use of a given technology; or intervene to facilitate the more rapid and effective development or adoption of new technologies. Interventions can mandate certain technological solutions to problems (e.g. seat-belts); regulate the use of certain technologies (e.g. recombinant DNA technology); or use technology as a means of intervening on a matter that does not appear intrinsically technological (e.g. use of large-scale data analytics to manage the spread of a disease). All such actions are called *technological interventions* in this report.

There are many types of technological interventions. Table 7 lists some examples.

Type of intervention	Description and examples
Regulation and standardisation	For example, are new regulations needed for emerging technology? [723,724]. Technologies can be regulated in many ways. Beyond formal government mandated regulation, standardisation processes can be very effective interventions (having both positive and negative effects).
Direct funding, adoption, investment or divestment	Governments or businesses can intervene by simply adopting new technologies on a large scale. Or they can fund technology development that facilitates its widespread deployment. Citizens can pressure public institutions to divest their investments in harmful technologies, e.g. the move from fossil fuels to renewables [521].

Cultural change / inspiration	Changing the way certain technologies are understood can have an effect on adoption – evaluating technologies in a broader context (for example looking at the harm done by alternate technologies) can change attitudes and drive adoption.
Innovation policy	Addressing the difficulty appropriating the economic returns of early stage technology development by direct funding, reform of patent systems, or open data policies can have large effects on new technologies.
Indirect interventions	Taxing negative externalities (Pigouvian taxes) can change the net cost of certain technologies, and motivate further development or adoption. Ensure new and minor players have an equivalent voice, and not just the current dominant players. A government can mitigate against one of the main sources of technological inertia [512] – the power of dominant players – by allowing others a voice. Education and training policies have a large impact on skills, which is central to technology creation and adoption [55,435,919]. Infrastructure investments (such as the National Broadband Network) can facilitate the development and adoption of a range of technologies that necessitate adequate infrastructure.

Table 7: Examples of types of technological intervention

Technological interventions are at least as complex as technological impacts which, as seen in earlier chapters, are both positive and negative ('benefits' and 'costs'), complex, context dependent[71], differential (affecting different groups of people differently), contingent (upon other impacts), often not easily understood using pre-existing categories (such as 'industry sectors'), take a long time to be realised, can be substantially influenced by perception, path-dependent, prone to lock-in, have no single easy to agree cost, have costs and benefits that can appear much later, sometimes beneficial, sometimes harmful (typically both simultaneously), hard to predict and even hard to retrodict. These manifold complexities are what make the evaluation of technologies and the design of technological interventions so challenging.

7.1 Difficulties of technological intervention

The difficulties encountered in how technology is understood and evaluated recur when designing interventions. These difficulties include the effects of uncertainty, over-determination, and unintended or unanticipated consequences.

The uncertainty involved in accurate costing and prediction of technology impacts are challenging for most technological interventions (Section 2.9.1 and Chapter 3). Whether an intervention is desirable typically comes down to cost (Section 6.4.4). Even specific technological *projects* are difficult to cost accurately, and the assessment of the desirability of a given technological intervention can be very dependent upon discount rates, for example. Any technological intervention inherits this difficulty both with costs and benefits. Many of the positive effects one may wish to achieve with a technological intervention are difficult to measure, and have the added difficulty of a substantial delay between intervention and effect. The uncertainty of when a technology will become widespread causes additional difficulties for planning technological interventions.

[71] An important aspect of context dependence that warrants singling out is the 'ecosystem' into which any technological development or intervention must feed – for example without the right industry receptors, no amount of R&D will realise value in Australia; conversely, if the R&D performed does not align with industry strengths, then there will be poor interaction. These factors, like the others listed above, all point to the need for proper experimentation – see Section 7.6.

Many technological interventions are either over-determined or undeterminable. Over-determined interventions include those that purport to single-handedly cause a change to a complex situation independent of other parallel policies or interventions. Undeterminable interventions are those whose effect cannot presently be accurately understood. Technological interventions generally require some form of experimentation to learn about the impacts. For example, Australia's carbon tax [1055] was a technological intervention in the form of a Pigouvian tax (Table 7) which sought to put a real price on the negative externality of carbon pollution, making the methods that do not produce as much pollution cheaper by comparison. By its very design, this would push up electricity prices due to the carbon pollution component of electricity generation. It was claimed by some that the carbon tax was the sole reason for higher electricity prices. It seems that over-investment in transmission infrastructure accounted for a larger component of the price rise [77,78,489]. This example illustrates that it can be difficult to unambiguously determine what effect can be ascribed to what cause, especially when transparent cost-estimates are not available, or when they are poorly communicated.

Unanticipated and unintended consequences of interventions will always occur because of the impossibility of predicting all impacts accurately (Chapter 3). Sometimes, the unanticipated consequences of deploying a technology outweigh those that were intended. Examples from the past (including DDT, thalidomide, global warming due to fossil fuels) show that these consequences can be severe [479,1033]. When something is unanticipated, one can only adapt when it does occur.

7.2 Improving the quality and impact of technological interventions

There are a number of approaches that can lead to better and more effective technological interventions including: devolving decisions, taking an extrinsic approach, and using open and transparent information.

Devolve where possible

Given the complexity of technological change it is impossible for a single body to stay up-to-date with all technological advances. This reasoning has driven the UK government to appoint a chief scientist within each department, rather than centralising all the expertise in one office [440,1070]. Technological interventions need expertise that understands both the local context and the technical basis of the technology.

Take an extrinsic approach to technological intervention

Interventions should not be predicated on technologies that are labelled 'good' or 'bad'. More effective interventions focus on the effects that result from the use of the technology in a particular context, not the technology itself. For example, the regulation of 3D printed guns should focus on the use of the gun, rather than the printer (Appendix C.1,[541]), to reduce sulphur dioxide emissions it is more effective to regulate the amount of emissions not the particular method or technology to be used (Appendix C.2, [930]). Rather than worrying that high penetrations of solar technology adoption which is variable due to clouds, will lead to unreliable electrical supply (relative to, say, coal [282]), intervention should focus directly on the desired outcome (that is, adequate supply reliability[72]).

Transparency and open access to information can improve innovation capacity and governance

Technology depends upon knowledge, and greater and open access to information and knowledge can aid technology adoption and development [600,710,811]. The flow of technological knowledge facilitates open innovation, which is the basis for the localised nature

[72] Germany, which has the highest penetration of renewables, also has the most reliable electricity supply [345]. This is not to imply some simple causation; simply to observe the often claimed incompatibility between renewable energy sources and reliable supply is no simple or fully determined.

of technology development [178,179,971]. Open standards counter the 'authoritarian technics' of Lewis Mumford [734,921]. They arise in part from ordinary citizens' desire to wrest control back into their hands [1104]; see also Appendix C.9. Open access to data can both aid technological innovation as well as enhance participatory governance [1029,1064].

The following points have potential to substantially influence the effectiveness of technological interventions: creativity and tinkering Section 7.3; education for adaptability Section 7.4; attitudes to failure Section 7.5; adaptive experimentation to enhance new technology adoption Section 7.6; modularity, standards and interoperability Section 7.7; regulation and mechanism design Section 7.8; and government investment in technological research and development Section 7.9.

7.3 Creativity and tinkering are essential skills for new technologies

Creativity is central to technological change; it can be encouraged and enhanced by providing greater opportunities for hands on tinkering and building at every stage of training and education for all Australians.

The transmission of skills is central to the economic impact of knowledge [216]. Hence motivating prospective students to acquire advanced technological skills can be economically valuable[73]. The skills necessary in society to deal with the uncertain nature of technological change mirror those required for professional technology creators (e.g. engineers) who play such a large part in the development of new technologies. This is not to say that in order to use a mobile phone, a person needs the skills to be able to build it. But for a country to embrace mobile telephony, it needs people who have the skills to design, install and maintain the requisite infrastructure. These skills are little different from those needed to develop mobile telephony in the first place.

Inventions and innovation are useful to society but the reason technology creators *create* may not be purely utilitarian. Named long ago the 'instinct of contrivance', and inherent in the etymological derivation of 'engineering' from 'ingenuity', a major motivation for inventors is the 'love of inventing' rather than searching for the solution to a problem, or financial gain[74] [916,1030]. The skills needed for technological creation and engineering include deep scientific knowledge, understanding of business and entrepreneurship and perhaps most importantly the ability to deal with uncertainty and open-ended design problems through 'optimism and

---

[73] Tankersley [1023] showed (with respect to the US economy) that every dollar a worker earns in a research field spills over to make the economy $5 better off. In contrast, every dollar a similar worker earns in finance comes with a drain, making the economy 60 cents worse off. There are rational taxation design strategies that could substantially influence the relative proportion of people attracted to science and engineering compared to derivative and apparently harmful financial markets [627].
[74] Rossman listed answers given by 710 inventors he surveyed about their reasons for inventing [916]. The answers were as follows:

Love of inventing	Desire to improve	Financial gain	Necessity or need	Desire to achieve	Part of work	Prestige	Altruistic reasons	Laziness	No answers
193	189	167	118	73	59	27	22	6	33

Later studies comparing independent inventors and professional research scientists demonstrated: researchers and inventors score abnormally high on aesthetic personality values – they value beauty and elegance for its own sake, like many other creators [666]; they are motivated by intellectual challenge, independence, with 'an important role of especially those motives that are nonpecuniary' [935] and are *intrinsic* [227]. The well-known psychology of researchers and inventors is why attempts to motivate inventors by control or financial incentives does not work very well – see Linda Butler's analysis of the lack of evidence that performance based research funding works in [786]. See also the discussion in Chapter VI of [80].

resilience in problem solving'[75] [648] (page 73). The creative aspect (manifest in the joy exhibited in the TV show Mythbusters [1071]) is what excites students, and many engineering professionals have recognised the imperative. Ellen Kullman, CEO of du Pont de Nemours and Company, and Charles M Vest, President of the US National Academy of Engineering, stressed the need to

> recast engineering as inherently creative and concerned with human welfare, as well as [being] an emotionally satisfying calling [741].

The need for engineering education to include creative and design-oriented foci has been long recognised[76] [616]. However progress remains slow[77], and one regularly sees urgent calls for reform in this direction both overseas [100,578,616,740,761,1157], and within Australia [834,1094].

There is a need for engineering education to include creative and design-oriented foci to a greater extent than at present by making creativity a deliberate focus [716,740,793,1059,1157], and complementing scientific facts-based education with hands-on tinkering [716,740,793,1059,1157], that is 'discovering the T and E in STEM'[78] or even recognising the 'craft' component of engineering [618]. This perspective has been eloquently articulated in [651]:

> Making things and then making those things better is at the core of humanity. Ever since early man started his first fire or clubbed his first seal, humans have been tinkerers. Farming, designing weapons for hunting, and building shelter were early forms of engineering. Tinkering was a way of controlling the environment and a vehicle for intellectual development. Throughout history, art and science, craft and engineering, analytic thinking, and personal expression have coexisted in communities, industry, culture, commerce, academia, and in the heads of creative people. Throughout history there has been an acceptance of the intuitive sense that peak learning results from direct experience.

This experiential approach through exposure to tinkering can add value at all educational levels – from K-12 [651] and through to university [740].

Ironically, within Australia the phrase 'Creative Industries' is used to refer to fields such as 'music and performing arts; film, television and radio; advertising and marketing; software development and interactive content; writing, publishing and print media; and architecture,

---

[75] These skills rarely all coincide in equal measure within one person [363].

[76] Confer

> All of the advanced industrial countries comparable to Australia (United States and Canada, United Kingdom, Europe, Asia) favour similar kinds of curriculum reform, shifting from a heavy content focus in science or an instrumental approach to mathematics, towards inquiry, problem solving, creativity and critical skills. Correspondingly, all these countries are focused on establishing pedagogies that are student-centred and inquiry based, with support for a variety of student competencies, [648], page 112.

[77] See for example:

> Australia has a long standing commitment to inquiry based and problem solving pedagogies and scientific and mathematical literacy aims. Australian educators have been at the forefront in promoting these ideas internationally. *The problem, however, lies in the inertia of schools and teachers in adhering to traditional teaching approaches.* (italics added), [648] (page 113.).

[78] Charles M Vest, quoted in the preface to [498]. Vest has also said 'my primary advice regarding engineering education is that making universities and engineering schools exciting, creative, adventurous, rigorous, demanding, and empowering milieus is more important than specifying curricular details' [1096].

design and visual arts' [283], but *not* the creation of technologies[79], as though the creativity in science and the arts is somehow different [902]. Exposure to the 'T and E in STEM' within schools retains a strong science bias with little opportunity to get one's hands dirty[80] (that is 'providing freedom to tinker' [100]). Focusing upon the creative and tinkering aspects of engineering (technology creation), without diminishing scientific rigor in any way, would not only attract more students to the field, but would create better technologists and thus eventually better technologies. It could enable a broader view of technology education more generally:

> It may be that the nation would be well served if engineering came to play a larger generic role in professional labour markets. Such a change may hasten growth in female participation. But this would require a shift in the assumptions dominant in tertiary engineering programs [648], (page 85.)

New technologies require professional engineers and technologists for their *creation*. They also require a technologically skilled workforce for their *adoption* that understands technology in a deep and broad sense. Educating for skills in creativity and tinkering crucial [100].

7.4 Education for adaptability to technological change

Focus education on the skills needed for adaptation.

Beyond inspirational and creative aspects, one needs a workforce that will thrive with *tomorrow's technologies*. As has occurred in the past, and will no doubt occur in the future, old jobs will disappear. Rather than the out-dated phrase 'technological unemployment', it is more accurate to speak of 'occupational obsolescence' as 'obsolescence implies that something has happened to outmode a particular way of doing' [252]. The separation of workers from their jobs is not merely due to technological developments. It can also be due to demand shifts on product markets [252],Appendix C.7, [868]; see also footnote 4 in section 1.4.

A 1988 report from the US Office of Technology Assessment considered the employment impacts of new technology networks and concluded that:

> People most likely to prosper in these networks are protean – able to change, adapt to unfamiliar work, and learn new trades as a continuous part of working experience. The talents needed are not clever hands or a strong back but rather the ability to understand instructions and poorly written manuals, ask questions, assimilate unfamiliar information, and work with unfamiliar teams. In short, the new networks require the skills provided by a solid basic education. …
>
> Earlier economic transformations were associated with a major public investment in infrastructure: canals, railroads, electric lines, and highways. The transformation taking place today seems to require an entirely different kind of public involvement. An educated population is the most critical infrastructure of the emerging economy. It is critical for both the economic growth of the Nation as whole, and the success of individuals acting as either consumers or employees, [1078] (pages 12-13.)

Since it is difficult to accurately predict major technological changes very far in advance, the ability to adapt quickly is necessary. More empirical work on how best to train for adaptability (or 'life-long learning') is needed:

---

[79] Excluding engineering from 'those industries which have their origin in individual creativity, skill and talent and which have a potential for wealth and job creation through the generation and exploitation of intellectual property' [990] makes no sense, and this is at least recognised by some: 'The corresponding "creative class" hence includes aside from artists or bohemians also scientists, engineers, lawyers or economists' [800].

[80] Possibly reflecting Australia's inheritance of the English prejudices against trade and industry [1124].

> in a technologically progressive or dynamic economy, production management is a function requiring adaptation to change and that the more educated a manager is, the quicker will he be to introduce new techniques of production. To put the hypothesis simply, educated people make good innovators, so that education speeds the process of technological diffusion [758].

The challenge to be faced is 'the race between technology and education' [435], where the outcomes of the race are economic growth or low-wage jobs. Educated workers are more adept at implementing new technologies [81]. Furthermore technological change favours the more highly skilled worker [553] (Section 2.9.3); as James Bessen puts it, the problem is 'scarce skills, not scarce jobs' [109]. Although a traditional university degree is no guarantee of a being able to adapt to technological change, the ability to think in a non-routine manner is suggested as a key differentiator [435]. With few exceptions there is little empirically based evidence on how this is best achieved.

The interventions necessary were made clear in the recent SAF02 report on STEM education:

> The Asian countries in the present study, all very successful in PISA and where disciplinary knowledge is held in high esteem, report a shift in focus towards nurturing generic skills of creativity, problem solving, collaboration and higher order thinking. Part of this shift relates to a perception that teaching and learning in classrooms is too teacher-focused and does not allow students to develop the creativity and problem solving skills that will drive innovation, [648] (page 108).

Countries such as Korea have embraced a model that

> is intended to emulate the philosophy of past Apple CEO Steve Jobs, that infinite imagination and divergent thinking, more than technological advances or industrial structures, define success in technology, including engineering and engineering design, and innovation in science, [648] (page 108).

Finally, funding basic research is a key intervention that facilitates the necessary skills development (see Section 7.9). As Mike Lazaridis, founder of the company *Research in Motion* (creators of the Blackberry wireless device), said:

> The number one reason to fund basic research ... is to attract the very best researchers from around the world. Once here, they can prepare Canada's next generations of graduates, masters, PhD's and post-doctorates, including the finest foreign students. All else flows from this ... If you really want to understand commercialization, all you have to do is attend convocation at your local university [135].

7.5 Embrace failure, and learn from it

New technologies typically fail in a variety of ways. Acknowledging the possibility of failure, and dealing with it in an effective manner can achieve better technological interventions.

Nothing we design or make ever really works. We can always say, what it ought to do, but that it never does.
David Pye [863]

Altering any aspect of an existing policy regime, or policy innovation, contains a risk of failure. And risk averse governments are often happier do nothing or little rather than do something which might lead them to be blamed for a failure. [505]

New technologies are born imperfect. Their improvement takes time and many failures. Failure of a new technology can take many forms [261]. Often viewed as part of the evolutionary model of technology it is easy in hindsight to see failures as inevitable steps along a path that ends in a mature, polished and functioning technology [620] (Section 2.3). In this section 'failure' simply means failure to work as intended [863], recognising the inherent vagueness of this definition. Technological failure is a major reason for the difficulty of prediction – predicting that some form of a new technology will work is straightforward, but predicting that it will work well enough to be widely adopted is much harder (Chapter 3). Technologies that are a great success are rare, and no methods of forecasting can accurately predict these [437]. Engineers learn from technological failures in a manner analogous to how scientists learn when experiment falsifies a theory [996] (Section 7.6.4).

The very failure that makes forecasting hard allows new technologies to be perfected:

> Much of the knowledge used to design, construct, manufacture, and operate engineered facilities and products has been obtained from learning from failures [261].

Economists use the phrase 'learning by doing' [1043], but this abstracts away what is really going on. Mistakes get made with new technologies, and technologists and users learn how to fix them [828]. Failures are not typically the result of incompetence. It is impossible to foresee all possible problems: who would have foreseen the risk of death from rust in steel containers caused by oxygen depletion[81]?

Leaders are counselled to embrace failure: 'If you haven't failed, you haven't tried very hard' [103]. Top venture capitalists attribute their success to their capacity to deal with failure. Vinod Khosla, founder of Khosla ventures, said

> Our willingness to fail gives us the ability and opportunity to succeed where others may fear to tread [561][82].

> Our single biggest advantage may be the fact that we've screwed up in more ways than anybody else on the planet when it comes to bringing new technologies to market. That's a big institutional asset. Our hope is that we're smart enough not to repeat the old mistakes, just make new ones [827].

It is difficult to admit error or failure [946,1031]. Attitudes to errors and failures are culturally determined[83]. Cultural attitudes to failure are embodied in much of the red-tape that gets in the way of innovation designed 'to avoid being seen to stuff up, rather than assessing just how much that "stuff-up insurance" costs' [1107]. It is easier to explain away failures in terms of external influences or involvement of outsiders [85] than to learn effective lessons that can guide future behaviour. Learning from failure is indeed difficult and requires deliberate experimentation [161].

Cultural practices (such as the way newspaper report on technological failures) can serve to reinforce attitudes such as humiliation in the face of failure. There are processes and practices which can be adopted to improve the response to failures – for example medical doctors can

---

[81] Two workers died upon entering a steel container that had been sealed shut. The steel rusted so much that it consumed the free oxygen and the workers asphyxiated (see section 28.8.1, [571] (page 435)).
[82] See also [445] and [563].
[83] The anthropologist Homer Barnett has argued for the cultural basis of attitudes to failure [80]: 'The humiliation that failure brings is … to a large extent culturally determined.' He contrasts two groups – the Manus people of the Admiralty islands ('who train their children for self-sufficiency and self-confidence', and 'are not pampered or shamed when the fail … [so that] the Manus child enters adolescence without feelings of inferiority'), and the Palauans whose timidity he ascribes to a lack of self-confidence and readiness to feel humiliation upon failure.

learn from the approach to error and failure that has been refined and systematically adopted in aviation [481]. However these process and practice alone do not solve the problem:

> The most important reason physicians and nurses have not developed more effective methods of error prevention is that they have a great deal of difficulty in deal with human error when it does occur [602].

Just as important as processes, is the *subjective feeling* of the actors involved – whether it is the doctor whose patient dies [1153], or the entrepreneur whose technological investment fails [42], changing the way errors are thought of, *and felt*, is central to being able to better respond when failures occur [1115]. The medical community has recognised this:

> When all else is said and done, the medical community must accept error as a community problem that is solved jointly [810].

> The most fundamental change that will be needed if hospitals are to make meaningful progress in error reduction is a cultural one. Physicians and nurses need to accept the notion that error is an inevitable condition, even among the conscientious professionals with high standards. Errors must be accepted as evidence of system flaws not character flaws [602].

If failures arising from the development and adoption of new technologies were viewed as system flaws (to be fixed) rather than flaws in the characters of the actors involved, it could encourage people to try out new (and risky) technologies. Furthermore, if education systems encouraged the 'struggle' one needs to face up to in the presence of failure, there would be less negativity associated with such struggle[84].

Governments can play a central role in encouraging experimentation and entrepreneurship. In the same way that a welfare safety net can avoid fear of technological change (by looking after workers whose jobs become obsolete), it can encourage entrepreneurship: 'When governments provide citizens with economic security, they embolden them to take more risks' [388].

Embracing failure is problematic for governments even when they are attempting to support innovation:

> I have spoken with officials with research funding programmes … in Australia who have acknowledged that despite the brief for their programmes, they are 'not very innovative'. Instead, they are forced to fund mainly safe projects, for fear of the consequences of 'failure' [827].

As explained in the UK Government's paper on improving government's approach to risk, the media tends to greatly amplify government failures [1068]. They observe 'the culture within government has often been characterised as being risk averse, lacking in innovation, and excessively concerned about failure and blame' [1068]. In Australia one need only think of Pink Batts and the NBN to see the extent to which two inherently risky enterprises are viewed primarily as a vehicle to assign blame. The Pink Batts scheme had a substantially better *relative*

---

[84] Consistent with Barnett's observations in the previous footnote, psychologist Carol Dweck has demonstrated that people with a 'growth mindset' (whereby they *expect* to fail, but will learn from that failure) maintain their confidence (and effectiveness) in the face of failure better than those with a fixed mindset (who believe that abilities are innate and fixed, and that failure on a task is a poor reflection on the individual) [317]. Dweck's work has formed the basis of educational interventions that help individuals move from a fixed to a growth mindset regarding skills particularly relevant to technology, such as mathematics – see [488] (pp30ff) with actionable recommendations:

> Teach children the values that are at the heart of scientific and mathematical contributions: love of challenge, love of hard work, and the ability to embrace and learn from our inevitable mistakes.

safety record (normalised per number of installations) than previously was the case. However, because of the large increase in numbers of installations, the *absolute* number of bad incidents rose[85]. Similarly, the NBN interim report was heavily focussed on assigning blame, with little contribution to rational progress on a complex, uncertain, risky technological project of national importance [958]. Governments and media struggle with the fact that even with the best 'risk management', things will still go wrong. There will be failures, and they will sometimes cause harm. The challenge is to learn from them [261,571].

A first step towards experimental government is being able to admit when things do not work out: 'Financial Times economist Tim Harford has also called for an annual award for politicians who admitted they got something wrong, learned from their mistakes, and completed a policy "U–turn"' [137]. Karl Popper's version of utopia is one where politicians compete with each other about how many errors they can admit [847]. Such a vision is indeed a desirable, albeit utopian, goal.

7.6 Experimentation versus traditional policy interventions

Since technological change is so hard to predict, policy interventions predicated on prediction and fixed polices will not be as effective as policies that have rapid experimentation cycles. Best-practice experimental methods can be translated from science to technological interventions.

We should not try to design a better world.
We should make better feedback loops.
– Tim Harford [473]

If policymakers are serious about evidence-based policy, then experiments should be central to the development of policy and the selection of the best policy option, but often they are not.
– Gerry Stoker [1009]

Policy can refer to decisions regarding the adoption of a class of technologies, ways of regulating technology, as well as broader government policy such as the degree to which fundamental technological research is supported or large scale government investments in particular

[85] There is of course no contradiction here. But it is misleading to claim it was badly done from the perspective of a technological intervention A CSIRO report [532] provides detailed evidence; see also [1000]. Like any technological problem, one can view the numbers in several ways. When one intervenes in any technological system, there is a chance of causing a problem. Typically this is manifest early on and it is the basis for the 'bathtub curve' (or more precisely 'infant mortality') of reliability engineering [281]. This is why large systems are commissioned before put into use so that the early bugs can be ironed out. Thus one would expect that if there were problems with insulation installation, they would show up shortly after installation. The CSIRO study found this to be palpably true. But this was twisted into a negative (and thus means to blame) by journalists, perhaps to make a more compelling headline or to comply with editorial direction. For example [309] correctly stated

> 'A CSIRO analysis found homes insulated under the program recorded insulation-related house fires - in the first 40 days after insulation - at a level more than three times the long-term average'

but then interpreted this as something unusual and bad. Such early occurrence of problems is entirely generic and easily understood, and in fact the long-term problems caused by the scheme in question were much *less* than previously installed insulation. Again, rather than a rational analysis of a technological problem, the majority of what has been written about this scheme has been to assign blame, and the media's role seems to be merely one of blame amplifier and fact attenuator. The whole approach by Government to risk analysis and management has been criticised by the royal commission report – see [469] where it is observed that the same problems could recur elsewhere (and have nothing to do with political orientation, but everything to do with operation of the public service and program delivery).

technologies. By reframing the question 'what will the long term future bring?', to 'how can we choose actions today that will be consistent with our long term interests?' the RAND report, *Shaping the Next One Hundred Years* outlined a quantitative approach to long term policy analysis useful under conditions of deep uncertainty [605]. One can deal with the uncertainty via robustness (plans that work well enough regardless of which future comes to pass) or via adaptiveness (plans that can be changed on the fly as circumstances change).

The level of adaptiveness in policy or management can be enhanced by adopting some of the principles and approaches that technologists and scientists use in the face of uncertainty. Broader adoption of such practices can assist governments and other actors associated with technological interventions by recognising the failure is to be expected and not something that should automatically be viewed through the lens of blame [499,505]. All long-term decisions (whether to do with technology choice or more generally) have to grapple with irreducible ambiguity, uncertainty, unpredictability and (at least some of the time) inevitable failure [737]. In response it is best to predict where it is reasonable to do so, but primarily adapt as fast as possible [910]. In order to do this, experiment explicitly and keep an open mind. The latter being difficult[86], the focus of this section is experimentation. The notion of an experiment below is very broad and includes 'any planned inquiry in which there is a deliberate and reliable argument from error' [658], not just the traditional, formal, randomised controlled trials. The key thing is to expect error or failure *in advance* and furthermore specify (in advance) how one will learn from that.

The approach outlined below as a way of developing policies for technological intervention when predictability is limited, and uncertainty is pervasive. Recognising scientific knowledge never is certain is important: pretending that it is certain leads to unrealistic expectations when errors do occur. In response it is important to explicitly adapt policies rapidly [698].

In the context of technological interventions, it seems more valuable to explore multiple options in parallel, regularly monitor and measure progress, re-evaluate periodically and expect to be wrong often. Central to this approach is viewing the entire process of any technological intervention as an *experiment*.

7.6.1 The experimenting society

The idea of interventions as experiments is not new, but without some precision, many things can be called an experiment [451]. Donald Campbell[87] wrote of 'reforms as experiments' in the late 1960s [157] with the idea of extending the 'logic of the laboratory' to larger social experiments [259]. The experimental approach has been encouraged in economics [129,251,474,614] and has been singled out as the key distinguishing feature of capitalism that has led to greater economic performance [909]. Many innovative companies embrace deliberate experimentation and associated rapid failure cycles as the way to make faster technological advances [161].

---

[86] Arthur C Clarke illustrated the difficulty of keeping an open mind regarding technological change as follows:

> One can only prepare for the unpredictable by trying to keep an open and unprejudiced mind - a feat which is extremely difficult to achieve, even with the best will in the world. Indeed, a completely open mind would be an empty one, and freedom from all prejudices and preconceptions is an unattainable ideal. Yet there is one form of mental exercise that can provide good basic training for would-be prophets: Anyone who wishes to cope with the future should travel back in imagination a single lifetime-say to 1900-and ask himself just how much of today's technology would be, not merely incredible, but incomprehensible to the keenest scientific brains of that time [189].

[87] See also [158] and [312]. A recent experimenting society work around the world is summarised in [137]. The use of experimentation in economics more broadly has become more widespread [380,455].

The basic idea of experimentation is simple[88]; the challenge is doing it well: 'most ameliorative programs end up with *no* interpretable evaluation' [157].That is, the experiment may be done, but not done in a manner that allowed a useful evaluation of its success. Experimentation may be done poorly because the actions are advocated as though they are sure to be successful, rather than expecting *a priori* that some may fail. This has the consequence that the advocates will fear failure and thus be incentivised to ensure any evaluation is as ambiguous as possible to control what may be said of their failure. Campbell's suggestion to deal with this is also readily translatable to the challenges of adopting new technologies. It is to shift from advocacy of a specific reform (say the adoption of a specific technology) to 'advocacy of persistence in alternative reform efforts should the first one fail'[89] [157,380,455].

Of course this precept does not provide complete guidance, and there are many threats to the validity of such experiments (some 15 are listed in [157]. However, none of this affects the conclusion relevant here: approaching the question of adoption or use of a new technology as an experiment is much better than seeking perfection because:

- It forces a focus on the problem to be solved, rather than trying to pick the technology winner at the outset; by changing the question from 'which technology to pick?' to 'how to detect which of many possible ones are working well?', the power of parallel exploration is harnessed, and the traditional problem of picking winners is avoided [595].
- If the technology does not achieve the desired goal it is psychologically and socially easier to try something else.
- If one takes the experimental stance, one may be more willing to do honest evaluations, which will assist in detecting failures early.
- The experimental approach is *organised scepticism* [682] from a *problem-centred* rather than *solution-centred* perspective [313]. It helps avoid creating 'trapped policy makers' who are 'so committed to favoured theories of policy that they see no need for analyses which might challenge their assumptions' [313], and embraces George Box's view that:

  > To find out what happens to a system when you interfere with it, you have to interfere with it (not just passively observe it) (quoted in [313]).

The hallmarks of a society that embraces technological change, using an experimental approach, would include being:

- Active: preferring active exploration over inaction.
- Honest: committed to reality testing and self-criticism to avoid self-deception.
- Scientific: in the sense of open criticism, experimentation, and willingness to discard theories that have been experimentally falsified.
- Accountable: results need to be made transparent.
- Decentralised: autonomy and diversification facilitate the conduct of multiple parallel experiments [158].

---

[88] A four step description is:

- Take small steps
- Favour reversibility "the first rule of intelligent tinkering is to keep all the parts"
- Plan on surprises (so design in flexibility)
- Plan on human inventiveness (assume that those involved in a project later on will develop the experience and insight to improve on the design) [952] page(pages 344-5.).

[89] Campbell suggested the political stance could be 'This is a serious problem. We propose to initiate policy A on an experimental basis. If after five years there has been no significant improvement, we will shift to policy B.'

7.6.2 Experimentation is best facilitated by loosely-controlled decentralised groups

Progress in technology is largely determined by the number of successful experiments made per unit time.
– James Brian Quinn[90]

The experimental approach is greatly facilitated by plurality of actors and approaches via small independent groups because this maximises diversity. The 'somewhat untidy' [830] nature of such experimentation is a natural way of dealing with failure and the evolutionary nature of technological change [687]. Big advances come from small experiments that succeed (most of course fail): 'It's not just experimenting; it's thousands of experiments' [830]. These experiments need to be done at the front-line level; no single person at the top can comprehend the complexity [473]. Rosenberg and Birdzell conclude regarding *How the West Grew Rich* [915]:

> Experiment is almost always conducted on the smallest scale necessary to prove or disprove a point; and the experiment so pervades Western economies as to assure that a great part of their economic activity will be conducted on a small scale[91].

People who are further up an organisational hierarchy can find it harder to admit failure[92] - another reason why innovation is best done from the bottom up.

---

[90] Quinn [864] continued:

> Skunkworks help eliminate bureaucratic delays, allow fast unfettered communication, and permit the quick turnarounds and decisions that stimulate rapid advance. ...
>
> To further enhance motivation, interactiveness, and rapid progress, innovative companies also emphasize small teams working in a relatively independent environment. The optimum number of key players sought per team varies from five to seven. This number seems to provide a critical mass of skills, foster maximum communications, and allow sufficient latitude for individual creativeness and commitment. The epitome of this style is the 'skunkworks' – named after 'Kelly' Johnson's successful group at Lockheed – in which small teams of engineers, technicians and designers are placed together with no intervening organizational barriers to developing a new product or process from concept to commercial prototype stages.

See the discussion building upon Quinn's analysis in the National Academy of Engineering report *Profiting from innovation* [502], and a history of the skunkworks by its subsequent leader [530].

[91] Rosenberg has amplified this point elsewhere:

> There is an additional advantage to a system that encourages, or at least tolerates, multiple sources of decision-making. Not only do human agents differ considerably in their attitudes toward risk; they differ also in their skills, capabilities, and orientations, however those differences may have been acquired. This heterogeneity of the human input, insufficiently stressed in micro- economics, constitutes a valuable resource that is much more readily enlisted into the realm of potentially useful experimentation by an organizationally decentralized environment. An economy that includes small firms and easy entry conditions is likely to benefit from this pool of human talent far more than one dominated by centralized decision making. ...
>
> The willingness to undertake experiments in both the social and technological spheres depends upon some sort of limitation upon the negative consequences for the individual if the risky enterprise should fail, as it frequently did [909,915].

This is sometimes explained as 'design locally, execute globally' (as opposed to the traditional top-down 'design globally, execute locally') [316], and is encouraged as an essential way of implementing design thinking: 'fail-early, fail-often' is best done in small groups [143].

[92] Sydney Finkelstein investigated major failures at over 50 companies:

> The higher people are in the management hierarchy, the more they tend to supplement their perfectionism with blanket excuses, with CEOs usually being the worst of all. For example, in one organization we studied, the CEO spent the entire forty-five-minute interview explaining all the reasons why others were to blame

The psychology of why such loose control is necessary is also well understood. The type of person who makes the advances that create economic wealth is typically a revolutionary. As Rosenberg and Birdzell say:

> Innovation is a form of revolt against convention, and it may be assumed innovators are more individualistic than most other people [360,915].

The people that create and adopt new technologies need to be managed appropriately; this is an important control action available to businesses and governments keen for the benefits of new technologies. As renowned management scholars state [434], one cannot inspire or lead such clever creative people by telling them exactly what to do and how they should do it, nor by setting numerical KPIs or performance bonuses. Deci, Amabile and others have assembled overwhelming empirical evidence that you simply will not get the best out of creative people by trying to manage them with KPIs and incentives[93]. In fact you will kill the creative spark:

> Creativity is undermined unintentionally every day in work environments that were established – for entirely good reasons – to maximize business imperatives such as coordination, productivity and control [20][94].

The creative people that generate technological advances are motivated primarily for intrinsic reasons (Section 7.3). It is now well documented that offering *extrinsic* rewards as a motivating factor to people that are already *intrinsically* motivated to perform a task, decreases their motivation and leads to worse outcomes [255]. As Harvard business school professor Teresa Amabile has written:

> Management is widely viewed as a foe of innovation. The thinking goes that too much management strangles innovation (just let a thousand flowers bloom!). But we have found a much more nuanced picture. You really *can* manage for innovation, but it starts by knowing what drives creativity in the people who generate and develop the new ideas that, when implemented, will become tomorrow's innovations. *Unfortunately, too many managers unintentionally kill innovation because they rely too heavily on carrots and sticks to motivate employees* [20] (italics at the end of paragraph added).

> for the calamity that hit his company. Regulators, customers, the government, and even other executives within the firm – all were responsible. No mention was made, however, of personal culpability [360].

[93] Confer

> There is much to be said for the strategy of focusing on the quality of life policies that can attract smart, entrepreneurial people. *The best economic development strategy may be to attract smart people and get out of their way.* This approach is particularly appealing because the downside is so low. What community ever screwed up by providing too much quality of life? … There is a robust link between educational institutions and certain types of high return entrepreneurship. The history of Silicon Valley would be totally different without Stanford [428] (italics added).

This is based on work that demonstrates the importance of large numbers of small firms (much more so than city demographics or 'culture of entrepreneurship') as a key causal factor in promoting entrepreneurship – in other words, many small experiments [427].

[94] This has been demonstrated in a compelling fashion in the specific context of research [58]. By comparing the long-term scientific *impact* (not mere 'excellence') of research funded through two different mechanisms, they showed the impact effect of autonomy. They compared results obtained via traditional National Science Foundation grants (with its concomitant bureaucratic controls) with those obtained via the innovative Howard Hughes Medical Investigator program, which bets on individuals and encourages them to take risks and follow their noses. The evidence is clear: the program led to substantially greater research impact.

A challenge for managers and governments is that full knowledge and control is antithetical to the type of creativity one needs to invent the future:

> The fact that a climate favouring creativity and entrepreneurship requires toleration of ignorance in the service of freedom. Insistence on full knowledge and control eliminates the latitude for creativity [856].

This situation, known as Mattera's dilemma[95], is related to the fact that large-scale technological changes are indeed revolutionary. The Industrial Revolution and related major changes are called 'revolutionary' for a reason [382,570,622,826]. Looser controls, a high degree of openness, tolerance for ambiguity, randomness of communications (as opposed to sticking to the pathways imposed by formal organisational hierarchies) and communication as consultation rather than command, are summarised neatly as 'organised disorganisation'[96].

7.6.3 Entrepreneurship as experimentation

Facilitating experimentation facilitates entrepreneurship. Much entrepreneurship involves technological change, and a lot can be learned about technological experimentation from entrepreneurs. The 'entrepreneur as experimenter' provides an elegant solution to the puzzle of entrepreneurial behaviour – they are all conducting experiments, most of which will fail [42,561] 'the prerequisites for entrepreneurial activity are a combination of highly uncertain returns that do not have an objectively known probability distribution, as well as the entrepreneur's skill in perceiving opportunity more clearly than others' [42,575].

> Entrepreneurs seek to speed up the testing of business ideas as much as possible, and when one fails, they rapidly move onto the next experiment: 'the uncertainty that surrounds most innovations and most new ventures can be significantly mitigated by comparing the plan on the table to other businesses already in existence' [732].

Financers of entrepreneurs are adept at recognising a failed experiment early on; indeed the ability to detect such failure is a competitive advantage:

> Venture capital firms that shut down more ventures do not necessarily perform worse, and, in fact, some of the best venture capital firms have among the highest rates of abandoning projects—in part because their skill at designing experiments and acting upon the results allows them to pursue more aggressive strategies and enter into more uncertain domains [561].

---

[95] 'Mattera's Dilemma [977]
is an example of a conundrum in social regulation that has both trade-off and dilemmatic components. The trade- off arises from the fact that a climate favouring creativity and entrepreneurship requires the toleration of uncertainty in the service of freedom. Insistence on full knowledge and control eliminates the latitude needed for creativity. The dilemmatic component arises from the fact that the greater the attempts to regulate behaviour, the more reactive people become and the more they attempt to generate uncertainty in the would-be controllers by withholding information or giving false information. If both parties pursue their self-interests, then the end result is a system of constraints and controls built on disinformation' [68].

[96] Klein explains 'organised disorganisation' as follows:
'What, then, does it mean for a firm to conserve its ability to engage in dynamic behaviour? As a result of a long-standing interest in trying to understand why some research-and-development organizations are more successful than others, I have found that the more successful ones defied what I had been taught about rational behaviour. On the basis of the classical theory, a rational planner would plan his system in detail from the beginning to make best use of existing knowledge. However, the more successful research-and-development organizations do not plan their systems in this way. Rather, they concentrate their attention on a few key features of the new system – and are very vague about the detailed optimization problems that system planners are said to thrive upon. Indeed, the people involved insist that only amateurs start with detailed system designs ... The most important fact about a world of strong uncertainties – a world in which there are no permanent truths – is that micropredictabilty and stability cannot be preserved' [570].

Recognising the central role of experiments in entrepreneurship and the concomitant centrality of failure is key to country differences concerning entrepreneurship, especially regarding failure (bankruptcy) [97]; foreigners flock to Silicon Valley to find 'the freedom to fail'.

Of course failure is not the goal; but 'while small firms may fail more frequently, they are also likely to introduce more innovative products' [607]. It is the appetite to do something more radical and risky that makes risk-seeking entrepreneurship central to rapid technological change.

The advice for governments is clear:

> [T]aking the experimental perspective seriously suggests that it is a poor idea for government to seek to pick and promote individual firms. After all, even the most-experienced venture capital firms have substantial success in only one of every ten investments they pick, so we shouldn't expect inexperienced and possibly not-very-objective politicians to do better. Indeed, one of the features that make market-based economies better at commercializing radical innovations is the decentralized and parallel nature with which new ideas are tested. Politicians also have greater difficulty terminating projects—that is, telling taxpayers that legislative decisions have spent their money with little or no return. In our experience, most economists buy into this wariness of policymakers acting as a venture capital firm, and many go a step further and caution against picking an individual sector or industry to support [561] (page 43.)

Likewise it is a poor idea for governments to pick and promote specific individual technologies, even though they should embrace broad classes of technologies such as general-purpose technologies. Governments, businesses and individuals can profitably apply the 'fail-fast' strategy that entrepreneurs routinely embrace into the adoption of new technologies.

7.6.4 Learn from how scientists and technologists deal with mistakes

Our whole problem is to make the mistakes as fast as possible
– John Archibald Wheeler [1122]

The approach taken by scientists and technologists in discovering scientific knowledge, or building new technologies, can be adapted to the challenges and uncertainty of technological adoption and intervention. Science advances when scientists admit what they do not know and when they turn that into a targeted research program [901].

> It is socially acceptable for a scientist or researcher to say, 'I do not know,' but it can be occupationally terminal for public administrators and politicians in some circumstances [1009].

Experiments do not guarantee the correct uncovering of causality or the best outcome first time around but they can provide a frame within which to act [1008]. Experiments can be used to both refine the technology itself but also is routinely done at a grand scale throughout the economic market place [915].

Experimentation can be a powerful way to deal with uncertainty surrounding the adoption of new technologies.[98] Using the method of multiple working hypotheses avoids picking a winner

---

[97] There are substantial differences between the ways European countries treat insolvent entrepreneurs – sometimes viewing them as criminals, even though only a tiny fraction of bankruptcies involve any fraud at all. According to figures sourced from the European Commission, the USA will usually discharge a bankrupt person from debts in under a year, but in Germany it takes around six years and in France nine years. There are also substantial differences in labour laws [1036].

[98] 'Program administrators must be encouraged (or even forced) to employ experimentation as means for innovation. This is less a matter of changing the corporate cultures of organizations responsible for program implementation than it is a matter of demanding innovation on the part of these parties' [1097].

and more importantly avoids the challenge of letting go of favoured theories (or favoured technologies)[99]. Economist Paul David argues that public policy should work to counteract any premature commitment to one particular product or technical standard before there is enough learnt about potential effects and applications of that particular technology [249].[100]

The best science learns as fast as possible what does not work through a series of decisive experiments – experiments designed to find what is wrong or what does not work. Scientists are exhorted to ask 'But sir, what hypothesis does your experiment disprove?' [836]. Rather than viewing failure as an unfortunate event that sometimes arises, instead it is considered a design goal – experiments are not valuable if they do not show something failed.

The focus on falsification lies at the very heart of science and is equally effective with new technologies and other form of policy intervention [845] (see section 7.6.5): one cannot predict whether a given technology will work. Instead one needs to try it (taking all reasonable precautions one can), but if it fails, adapt appropriately. In order to do this, one does need to specify what it means to fail in advance.

Technologists have systematically developed processes that deal with the problems that arise due to the inability to predict future technologies accurately. Under the general heading of 'agile' methods, these have long been used in various areas of engineering [205] such as manufacturing [1155]. They are now popular in software engineering as a means to speed up experimentation and adaptivity [3,91]. The key values of agile development are all motivated by the problem of being unable to predict and plan well enough for more traditional methods (where one negotiates the requirements and then contracts to deliver them). Agile methods embrace adaptivity through four 'focal values'. The most important of which is responding to change over following a plan [3][101]. Similar principles have been proposed in the architecture of

---

[99] The best science tends to be problem oriented too:

> Beware of the man of one method or one instrument, either experimental or theoretical. He tends to become method-oriented rather than problem-oriented. The method-oriented man is shackled: the problem-oriented man is at least reaching freely toward what is most important. Strong inference redirects a man to problem-orientation, but it requires him to be willing repeatedly to put aside his last methods and teach himself new ones [836].

Renowned geologist Thomas Chrowder Chamberlin, writing in 1890, neatly identified the reason for pervasive confirmation bias:

> The mind lingers with pleasure upon the facts that fall happily into the embrace of the theory, and feels a natural coldness toward those that seem refractory [175].

Pragmatic technologists adopt such a strategy in creating technologies [75]. Given the complexities of evaluation of new technologies, such a pluralistic approach has much to recommend it for encouraging the adoption of new technologies.

[100] There is no reason to believe that government has any special ability to foresee future developments and yet all government decisions about which technologies are eligible for support, and to support particular projects implicitly makes choices about technologies [1146].The Grattan Institute suggests the best strategy for energy policy in the face of uncertainty is to support a variety of options. Over time this will be the cheapest way to deploy technologies and to see how well they work. Governments that legislate for an ultimate end goal (e.g. putting a price on pollution) allow businesses to determine for themselves how to achieve that goal. This approach minimises the need for government to predict the future and it provides businesses with certainty and flexibility [235]. Such an approach is used in the 30 year plan developed by the Queensland government to deal with the changing electricity network [270].

[101] The four values are

- Individuals and interactions over processes and tools
- Working software over comprehensive documentation
- Customer collaboration over contract negotiation
- Responding to change over following a plan

buildings where adaptation, rather than perfect planning and contractual lock-in, are proposed as ways of making better buildings (technology[102]) [17].

There are many variants, but the core of the scientific method recognises uncertainty, and embraces change and adaptability, rather than trying to avoid it through prediction and planning. Experimentation is not simply randomised controlled trials; but they are a particularly valuable form which has become increasingly adopted in technological development.

7.6.5 Randomised controlled trials

A randomised controlled trial utilises randomness to experiment with different treatments, policies or technological choices. A simple form is known as A/B testing [185,186]. Long used in the design of medical interventions, a set of possible choices is made available and randomly chosen, and the results are evaluated. The crucial value of randomisation is that it can avoid cognitive biases that arise when one presupposes the value of a given intervention [477]. Randomised controlled trials are valuable because they are conceived and declared to be an experiment before they are carried out. They have a predefined way of assessing failure. They are not a simple 'gold-standard' of how to conduct any experimentation as some have claimed [821]. In some situations randomised controlled trials can be useful in evaluating different new technology choices, but it should not be viewed as a one size fits all solution. Errors can occur in a randomised controlled trial, and even in medicine they are not used blindly [477].

For some, the concept of randomisation may seem like a hard political sell: 'You want me to tell the public that I have no idea what is the right thing to do so I am going to leave it to chance?' [1009]. Even when conducted properly, the evidence from a randomised controlled trial needs to be carefully interpreted:

> Evidence is bound to disappoint those who want conclusive proof from it. Evidence alone does not ensure wisdom or deliver something call 'objectivity' or 'the truth'. Evidence alone cannot quickly silence doubts (about climate change and the role of renewable energy sources, for example). Nor does evidence settle once and for all the value of a specific activity or policy (such as support for SMEs to drive economic growth). Evidence is always contingent on context, sources, perceptions and timing. Good evidence may be ignored, bad evidence may be used misleadingly. Knowing all this helps us to use evidence wisely [613].

7.6.6 Summary

In the face of what is ultimately irreducible uncertainty about technological change, the only thing one can do is to react. Systematic experimentation, entailing measuring broadly, making data widely available, the appropriate design of institutions ('institutionalising mindfulness') building an attitude to failure that does not disable or create despair; systematically reporting failures in a non-punitive manner; encouraging alternate and diverse frames of reference; and

---

Ironically such values have since been turned into heavyweight processes, and one of the original proponents of agile methods in software engineering has distanced himself from the agile movement. In doing so he has distilled the whole point being made here [1041]:

> What to do: Find out where you are; Take a small step towards your goal; Adjust your understanding based on what you learned; Repeat. How to do it: When faced with two or more alternatives that deliver roughly the same value, take the path that makes future change easier.

[102] Some architects stress the importance of 'post-occupancy evaluation' of a building – that is evaluating it after the building has been occupied [136]. The central idea is that the architect's initial design often fails; not catastrophically in the sense that the building collapses, but in the sense that the building (the technological artifact is not right) [350,852,853]. These lessons can be readily generalised to more general technological interventions [408]; the central idea is to return, measure and evaluate.

inculcating the flexibility to learn and adapt – one can better deal with technological change because one can adapt faster [1117].

7.7 Interoperability, modularity, and standards

Standards are a powerful intervention to achieve modularity, and assist in the parts-assembly nature of technology creation. Lightweight agile standards seem better suited to encouraging technological change than heavyweight complex standards.

The formation of standards is a key intervention that can speed up or sometimes delay technological progress. Facilitating agile standards and promoting open and interoperable platforms can facilitate technological change and trade, particularly information and communications technologies [1135].

7.7.1 Interoperability

Technologies are composed of parts, and furthermore new technologies need to be able to interoperate with old technologies. Interoperability is not merely connecting parts together, but making those parts work together (Section 2.5). Interoperability can be difficult to achieve - being able to plug a data-projector into a computer and have it work remains a fraught exercise. But there is much technological interoperability that is taken for granted – the worldwide telephone system, the electricity supply network with standard power outlets, standardised bolt sizes, and the ability to use any pot on any stove. It is the *failures* of interoperability that are noticed, such as aluminium pots which do not work on induction stoves. Interoperability is not just a technological problem – there are human and institutional dimensions to it [809]. The best level of interoperability is not necessarily the maximum, there are many reasons why some constraints on interoperability are desirable (privacy and security compartmentalisation for example) [268].

Interoperability through modularity and standardisation is well illustrated by the standardised shipping container[103] which greatly increases the efficiency of ocean transport, but does not solve all problems of interoperation [14,611]. There remains more to be done to ensure better interoperability across different transport modalities, for example through the growth of ‘interports’ (multiple transport nodes with contiguous hubs):

> Interoperability decouples markets by increasing the competition and decreasing the lock-in effects of intertwined markets. Interports are vehicles of interoperability; they decouple markets by enhancing the network effect and by increasing the variety and number of interactions between market participants [14].

7.7.2 Modularity

Technological modularity is the key to evolutionary combinatorial technological innovation [410,599,1091]. Modularity speeds up technological innovation in the same manner as it accelerates biological evolution, because it allows the independent design of different parts and the formation of new business ecosystems by offering opportunities for new firms to enter the market [65,190,815,939]. Much of the current success of Silicon Valley as a location for technological innovation can be explained by the very high degree of modularisation of

---

[103] The impact of which has been immense:

> A thing as simple as a standard-sized metal box, designed for interoperable handling and transportation, cut down on transaction and conversion costs so drastically, and reduced fiscal cost and risk in such improbable amounts, that it now made sense to ship them halfway across the world. By dissolving a great majority of the transport inefficiencies that had plagued the practice of loading loose cargo onto a ship essentially since the Phoenician times (the container box’s unitizing of cargo altered a system of piece-by-piece freight handling that had not changed much since the B.C. shipping cultures), the container box not only cut down on freight bills, but also saved enormous amounts of time [14].

computer technology, which allows for the rapid evolution and specialisation of supplier firms [67]. Modularity is no panacea, and there is no one right degree of modularity – there are penalties for too much or too little[104] [66].

7.7.3 The role of standards

Standards are a means of achieving modularity which facilitate the adoption of new technologies [108,896,1026]. Standards serve to coordinate multiple actors (e.g. different companies) in the development and adoption of technologies [940]. Standards themselves are a 'social' technology[105] [267,324]. They are neither simple, nor decoupled from vested interest [471,707]:they do not follow a simple linear development process, nor are they a universal good [347,377,471]. They are socially shaped (often adversarially), and live in continual tension with flexibility [412,472,962]. They can facilitate technological and economic advance or be the vehicles for the technological momentum and inertia that slows the adoption of new technologies by self-interested manipulation from large players and interaction with intellectual property rights [247,508,706,1054]. Standards are an important means of technological intervention.

The desirability of many simple standards, rather than one large comprehensive one, is apparent when considering the 'internet of things' – the use of cheap wireless networking technologies to connect a diverse range of physical things, from refrigerators to milk cartons [577]. It is not sufficient that the signals technically can interoperate (for example by using the same radio frequencies). There needs to be 'semantic interoperability' so that different components can understand the messages, as well as organisational or systemic interoperability to allow multiple organisations to interoperate. No single standard can do this. Lots of little standards, experimented with by many people, are likely to lead to new products and services. The current state of the art (of the internet of things) is a 'standards war', with major players hoping to gain competitive advantage via large and incompatible standards [748,962]. As in the past, it is not obvious that the solution is heavy-handed government intervention [896], unless there is undesirable lock-in and inertia created.

Like other aspects of technology, standards are greatly affected by costs. The Universal Product Code (barcode) is now widely used in the commerce of goods, but is in fact delaying the introduction of more powerful tracking and identification technologies e.g. RFID tags [93,690]. Until the cost of RFID tags which offer richer functionality are reduced in price by another factor of 10, Universal Product Codes will continue to hold a dominant position.

The challenges of predicting the state of future technologies (Chapter 3) imply how one might go about enhancing interoperability in an evolutionary and experimental manner:

> In reality, the vast majority of interoperability that occurs into today's information economy happens in a completely natural, evolutionary fashion without any significant state intervention whatsoever. In countless small and big ways alike, interconnection and interoperability happens every day throughout society …

When in doubt, ongoing, bottom-up, dynamic experimentation will almost always yield better answers than arbitrary intervention and top-down planning [1040].

---

[104] 'Too little' is obvious: it means missing out on the benefits of modularity. 'Too much' is less obvious, and arises where in order to attain adequate performance the system designer needs to cross the modular boundaries. In telecommunications systems this goes under the name of 'cross-layer design' [991].

[105] The idea of a 'social technology' includes social routines and institutions. These play a central role in the adaptation to new technologies – the latest physical technology immured in an antique social technology will have little chance of success [757] and [242].

An evolutionary view of standards shows that while standards limit technological variety, they also allow for greater cross-over of ideas [688]. Ultimately standards evolve just like other aspects of technology, and thus exhibit the unpredictability and diversity of technology itself.

7.7.4 Problems with standards

Standards can sometimes freeze development [325], but open standards arguably are less prone to this problem [584].

Premature or localised standardisation can cause considerable harm [634]. The choice of a standard railway gauge is obviously necessary for making a railroad; but the choice creates huge path dependence over many decades, and is sometimes the result of random circumstance [860,861][106]. This is a relevant example for Australia where multiple railway gauges persist across states; this was recognised as a potential problem early in the process[107], but not acted upon:

> The estimated cost of remedying the resulting diversity rose, as equipment was purchased and track was laid, from £15,000 – £20,000 in 1853, when breaks of gauge were a distant prospect, to £2.4 million in 1897 and £12.1 million in 1913, when they were becoming costly. Efforts to resolve the diversity were long hindered by disputes over how the separate government-owned systems should divide the costs [860].

This case is complicated [276], but wanton exercise of power played a substantial role:

> The choice of a gauge of 5ft 3in for Victoria was due entirely to the Lieutenant-Governor's unfettered exercise of his authority [693].

More generally, and not irrelevant for today, (confer the political arguments about the NBN),

> those choices were part of a search over fifty years by government representatives seeking colonial identity/autonomy and/or platforms for election/re-election [694].

Although if unified early on, the benefits would have outweighed the costs, they no longer do, and Australia still has multiple rail gauges, although the interstate links have been unified [275,289].

Standards can be light and simple, or heavy and complex. A lesson can be learned from two styles of standards used in modern web services: REST (Representational State Transfer) and SOAP (Simple Object Access Protocol) [989]. REST has few actions, is stateless (that is there is no stored state within the protocol) and is widely used [358,817]. SOAP seemed a good idea when introduced, but primarily due to its complexity it has fallen from favour. The comparison between the two types is complex [818], but in a manner exemplifying what facilitates rapid technological change, the internet economy has heavily embraced RESTful interfaces due to their simplicity and statelessness, which is central to being able to compose many modular

---

[106] Puffert [860], reports

> The introduction of 4' 10" to Ohio was the result of buying a New Jersey locomotive 'off the shelf.' Promoters of Ohio's Mad River and Lake Erie Railroad were reportedly impressed with the novel whistle of a locomotive available as a result of a canceled order. They bought it and built their track to fit.

Least we laugh at the folly of ancients, one can readily find many modern technological artifacts purchased primarily on the basis of appearance [224].

[107] In the United States the problem was recognised, but not resolved, remarkably early. As Puffert relates [860], a journalist writing in 1832 said that:

> When we consider that most of the principal Railways now in progress … must soon intersect each other … we are forced to conclude that this discrepancy in the width of tracks, will ultimately produce an infinitude of vexations, transfers and delays which might easily have been avoided," as each company could have adopted "the mean width of the whole without any possible detriment."

As with other technological predictions, it is easy to recognise the validity of this in hindsight!

parts to make a larger system [507]. Encouragement of componentisation and modularisation through lightweight standards and gateways, could aid new technology development, assist smaller firms to innovate, and speed new technology adoption [685].

7.7.5 Governments and standards

Government's role in the development of standards is not simple. In the case of standardisation of mobile phone chargers, the threat of government intervention (by the EU), and subsequent (non-binding recommendations) led to eventual commercial standardisation in the face of a pervasive problem – the need for many different chargers for different models of phones [866]. With the threat of government intervention, industry converged on the micro-usb standard. The EU has explicitly welcomed the industry position that 'will not preclude innovation in the fast moving mobile phone market by fixing a certain technology forever' [866].

Governments play a key role in the setting and maintenance of standards, which is not to say they should always set them [394]. It is common for governments to encourage industry to develop their own, not least because they have the technical expertise to do so [61]. Merely agreeing upon a standard is sometimes insufficient[108]. Governments are exhorted to stay out of technical standards setting wherever possible, to help facilitate non-technical forms of interoperability (e.g. organisational, semantic and policy interoperability); encourage choice and plurality; and openness of innovation systems and standards formulation in a manner that balances the needs of intellectual property protection and innovation [1060].

7.7.6 Platforms and gateway technologies

Platforms and gateway technologies can help avoid some of the problems of standards. A 'platform'[109] (admittedly hard to distinguish from a 'system') is an ill-defined technology layer, upon which a diverse set of services can be built by others [201,485,1081,1159] (implying 'generativity' [1104] (page 111)). Digital platforms can enhance generativity by maintaining data portability and API (Application Programming Interface[110]) neutrality [1159] – that is, platforms do not mandate much about the other components that interact with the platform.

Platforms can either slow or speed technological progress[111]. Platforms can slow progress by lock-in of standards (such as the QWERTY keyboard) [34,217,243], or they can speed progress by being open for all and thus providing greater opportunities for innovation [169,181,267,348]. By focusing on the standardisation and sponsorship of platforms, governments can accelerate wider technological innovation [446,1081].

Gateway technologies can reduce the systemic resistance new technologies face and solve what seem to be intractable incompatibilities between differing standards by building bridges

---

108 Witness the complexities of governance arrangements surrounding the root nameservers (the top of the global hierarchy of domain name servers that manage the naming conventions for internet addresses) [589].

109 Nowadays often used solely with regard to ICT, older technological innovations can be viewed as platforms – for example electric motors [241] [122].

110 As Joshua Tauberer says, knowing what the letters stand for sheds no light on what it means.

> An API is a contract. Not legally, but technically. It is a commitment that a system will work in a certain way. There is a process in place. An API would say that if you visit a certain web address, you'll get a certain slice of the data [1029].

An API allows system designs to *rely upon* other systems to behave in a specified way in order to compose them to make a larger system.

111 The attraction of platforms to a business is that if they can achieve lock-in with a large user base, they guarantee a long-term steady revenue stream, as well as enabling others to achieve more:

> 'If there's one thing we learn from the technology industry, it's that every big winner has been a platform company: someone whose success has enabled others, who've built on their work and multiplied its impact' [780].

between different standards (Section 2.5). Economist Paul David recommends governmental support for R&D that can be focused on such gateway technologies because of the multiplier effect obtainable [244,470,708].

A recent local example of a gateway technology is the 'National Map' system, which is a federated webservice that makes diverse sources of public domain spatial data readily available to a user through a familiar web interface (see Figure 15) [767]. The key aspects that have contributed to its success are: it offers simple platform that allows data owners to publish their data; it does not try to do everything, in particular it does not host the underlying data, it merely provides a *gateway* to the data via a simple standard (RESTful); and, consistent with the agile principles described earlier, it has evolved rapidly. It is a powerful and valuable example of how gateways and platforms can speed innovation for the benefit of Australians generally. It also illustrates the benefit of long-term government support of R&D for general-purpose technologies (in this case ICT); see Section 7.9.3.

7.7.7 Summary

- Interoperability is central to the adoption of new technologies
- Modularity is the key to interoperability, and the design of any large technological system; it facilitates the development of rich and agile market structures.
- Standards aid modularity and hence interoperability and thus assist the adoption of new technologies. However, they can also lead to technological lock-in which can slow the adoption of new technologies.
- Standards can interact with intellectual property rights in complex ways. This underpins standards wars and related strategic behaviours by entrenched firms that are not in the public interest [394].
- Standards aid trade and hence adoption of international standards is preferable to developing distinct national standards.
- Gateway technologies and platform technologies are particularly valuable in supporting interoperability because they can work around the problem of multiple standards and avoid some of the problems of lock-in.
- Governments are not typically best placed to mandate suitable standards but they can facilitate their development and adoption.
- A larger number of simple and lightweight standards of limited scope has led to an explosion of innovation on the internet, and seems a valuable approach more generally to enable the adoption and development of new technologies.

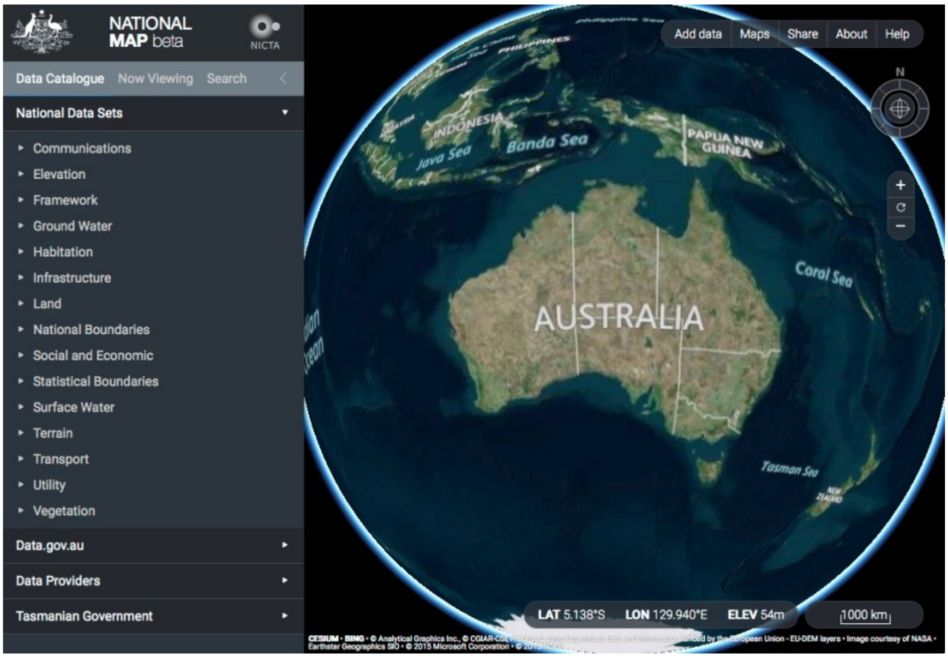


Figure 15 The National Map system developed by NICTA. This is a federated gateway that makes diverse sources of public domain spatial data readily available to a user through a familiar web interface. It has facilitated a much greater availability of public domain spatial data than was previously the case.

7.8 Regulation

Regulation is a crucial technological intervention. To promote technological change regulation should be focussed on the use of a technology, rather than particular aspects of a technology.

This section will discuss some of the ways in which regulation and technology interact. The report takes a broad perspective on both regulation and technology. Regulation creates limits or constraints, or allocates a responsibility through sets of legal rules established. Regulations are enforced by government to either constrain the actions of individual parties or place obligations to act on those parties. Different regulation is motivated by different and sometimes conflicting concerns.

To provide appropriate protection for consumers or broader society, some categories of technology will require more regulation than others. Well-designed regulation requires a balance between the risks and potential benefits of technology. With the benefit of hindsight, it is clear that the introduction of certain technologies in the past (with inadequate regulation) led to tragedy for both human and environmental health (e.g. DDT, thalidomide). Incidents such as these have led to increased regulatory controls for the acceptable levels of risk and benefit for food, chemicals and pharmaceuticals. For instance, pharmaceuticals require large amounts of long-term data so that government bodies can assess the risks and benefits of human pharmaceutical. New technologies, where the risks and benefits are highly uncertain (and potentially unknowable) create significant issues for the design of appropriate regulation. Government regulation of technology generally occurs upon commercialisation or mass adoption of a particular technology, through compliance, following specific events (e.g. regulation post disasters) or due to public pressure (e.g. Appendix C.4 [932]).

Regulation can be paradoxical:

> Well-designed and properly implemented regulation can bring about good results. Yet a critical assessment of how regulation can bring about beneficial ends and when it fails to do so is challenging. This is because the appropriate level of regulation considered necessary, when it is required and how it should be enforced is vigorously contested [458].

Risk, specifically who bears the risk, is often a key challenge in gaining consensus on a regulatory decision. The risk involved is a combination of actuarial, sociological and political risk. Actuarial risk is defined as risk assessment through evidence-based, independent and objective information. However, the driver of government policy development is highly dependent on sociological risk and political risk, which are strongly connected to public perception and uncertainty [458]. Australian regulation is also deeply connected to global regulation which never occurs on the basis of a single mechanism; there are dense webs of influence [134].

The competing motivations and influences in regulating technology require adherence to clear best practice regulatory principles.

7.8.1 The design of technological regulations

There are a few key principles that can guide the development of technological regulations [386], p269:

- Identify the underlying problem rather than the proximate cause of the problem. Often the problem is framed around the technology, for instance that a drone took a photo of my backyard, when in fact the real problem is a breach of privacy.
- Consider all possible technologies, and all means available to regulate.
- Assess the costs (including compliance cost) and benefits of the regulatory intervention (Chapter 6).
- Evaluate the effectiveness of the regulation after implementation [250].

There is a broad consensus on the best practice for regulatory design[112] and this can be applied to technology regulation.

It is intrinsically complex to analyse the need for, or the effectiveness of, a technological intervention. Given all the caveats outlined in Chapter 6 any decision should be based on evidence by measuring the effect of the regulation and adapting where necessary (see Section 7.6) [698].

---

[112] Policy makers from the Australian Office of Best Practice Regulation have created the following best practice regulatory principles. These principles are very broad and apply equally to the regulation of technology [233]:

1. Regulation should not be the default option for policy makers: the policy option offering the greatest net benefit should always be the recommended option.
2. Regulation should be imposed only when it can be shown to offer an overall net benefit.
3. The cost burden of new regulation must be fully offset by reductions in existing regulatory burden.
4. Every substantive regulatory policy change must be the subject of a Regulation Impact Statement.
5. Policy makers should consult in a genuine and timely way with affected businesses, community organisations and individuals.
6. Policy makers should consult with each other to avoid creating cumulative or overlapping regulatory burdens.
7. The information upon which policy makers base their decisions must be published at the earliest opportunity.
8. Regulators must implement regulation with common sense, empathy and respect.
9. All regulation must be periodically reviewed to test its continuing relevance.
10. Policy makers must work closely with their Deregulation Units throughout the policy making process.

7.8.2 Regulate the effects of the technology, not the technological artefact

Technological change leading to the use of emerging technologies can influence legal change just as legal change can influence technological change [725]. Understanding legal responses to technological change [723,724] leads to questions such as: are current regulations sufficient in dealing with specific emerging technologies?; are there new security threats enabled by new technologies?; are there community behaviours that need intervention? For example, vested interests preventing desired change, such as traditional energy companies who might oppose the development of alternative sources of energy in order to protect their own profits [512].

Regulation with a focus on the effect of using a technology, as opposed to the form of a technology, can often deal with emerging technologies[113]. New technology interacts with existing laws and regulations [721]. Most technologies sit comfortably within existing legal frameworks that regulate the liability of manufacturers, retailers and consumers. In some cases the existing laws and regulations can adapt to the new technology with relative ease, particularly through the use of common law as this focuses on specific effects due to the use of technology [722]. In other cases, new technology puts pressure on existing laws and regulations. Some examples are:

- When technology allows a new way to provide a service. For example, Uber, the internet-based ride-sharing system, is challenging some taxi industry, 'private vehicles and drivers using Uber's ride-sharing' app would be operating in breach of the legislative requirements in the ACT' [867]. However, the existing regulatory and legal regime sufficed when the first Uber accident occurred in Victoria.
- When the use of new technology affects the social acceptability or enforceability of existing law. For example, peer-to-peer file sharing and the development of digital entertainment products (such as film and music) have undermined traditional copyright laws. Some technologies have made these laws hard to enforce, and copyright owners are attempting to pursue their legal rights through the courts [869,953]. Technology has also either exposed the limited community acceptance of these laws as significant numbers of individuals ignore the relevant laws.The introduction of a fully autonomous vehicle might shift liability to manufacturers. This would change current insurance paradigms relating to personal transport vehicles (Appendix C.3 [931]).
- Technology can undermine regulations, and the rules may need to be redesigned or re-interpreted to deal with emerging technology or new uses for existing technology, for example by modifying legal frameworks, such as altering existing regulations, as is the case with nanotechnology [50].

Any intervention must also take the power of labels, perceptions and metaphors of technology into account (e.g. robots, GM crops, 3D printing). For example, humans are wired to anthropomorphise technology, which can have a significant effect on regulation. Popular media descriptions of 'traditional' robots can be misleading, such as robots can (and will) do everything, when in reality robots are becoming highly specialised at specific tasks. Robots and robotic technology are very much a part of modern society (a photocopier can be considered to be a robot) and will continue to be part of our lives in many forms (Section 5.1.6). There is a need to improve public understanding regarding the technical capabilities of technology. For instance, the false assumption that robots are just like people, also known as the android fallacy,

[113] Government has enacted laws specifically directed at technologies such as requiring health insurance organisations to provide cover for *in vitro* fertilization. They have also enacted rules aimed at coordinating the use of technologies, as in the case of traffic rules and technical standards [723]; For a description of different types of standards, see [993]. Examples of technologies that appear to warrant direct regulation of the technology itself are those that can cause great harm in the wrongs hands including nuclear technologies [41], genetic engineering [841], and autonomous weapons [37].

should be made clear. Legislation should address the function of the technology rather than its form [886].

Regulation, with a focus on the effects of using a technology and not the technological artefact/process itself, can protect the public and enable industry [725]. The best available technology regulations focus on a particular social problem (e.g. sulphur dioxide emissions - see Appendix C.2 [930]) rather than incentivise for a particular technology. This form of regulation encourages industry innovation to solve the problem in the most affordable way and incorporates the changing nature of social values and advances in technical capabilities. By choosing to regulate outcomes – leaving individuals and businesses to pursue alternative technological approaches to those outcomes – instead of prescribing the 'best' technology, governments and regulators can allow for unforseen innovations which may offer cheaper and better solutions. This is neatly illustrated in the emissions trading scheme implemented by the U.S. Environment Protection Agency (EPA) in the 1990s. The government announced its intention to reduce sulphur dioxide emissions by ten million tons per year by 2010.

> At root, what the emissions allowance market is doing, like any other competitive market, is generating information. It reveals how to reduce pollution in the lowest-cost way, as well as what the costs of reducing pollution actually are.
>
> The prices of the allowances surprised most observers, being far lower than expected. The surprise came because command and control had left everyone (except perhaps the polluters themselves) with a distorted impression of these costs. Before emissions trading began, the EPA estimated it would cost $750 to clean up a ton of sulphur dioxide. The electric-power firms claimed it would cost them up to $1500. The average price at which the allowances actually traded over 1994-1999 was about $150 [671].

This example illustrates that by focussing regulation on the problem to be solved, a diverse set of technologies can be inspired, created and used.

7.8.3 The effect of policy uncertainty on industry innovation – stringency, inflexibility and lack of information

When implementing regulations for emerging technologies a lack of clarity and flexibility will create additional uncertainty and slow emerging technological advance.

There are a number of ways in which government regulation can affect innovation, 'the commercially successful application of an idea, from invention, the initial development of a new idea, and from diffusion, the widespread adoption of the innovation', [39] (page 110). From an industry perspective, regulation can place a compliance burden on firms, which can cause them to divert time and money from innovative activities to compliance efforts. Clear regulatory direction for emerging technologies can spur innovative activity within industry.

Uncertainty typically precedes the implementation of regulation in response to a technological change [723].

> Policy uncertainty occurs when a firm or industry anticipates the enactment of a regulation at some time in the future and has a mixed effect on innovation regardless of whether the regulation is eventually enacted or not'. For example, if firms expect a change in the stringency of a regulation to require compliance innovation, then policy uncertainty may spur innovation prior to the regulation being enacted. Likewise, the compliance burden may affect firms prior to enactment if, in anticipation, they begin diverting resources toward compliance. That said, this behaviour assumes that the degree of policy uncertainty is not so large as to discourage business decision making entirely. If policy uncertainty is high and the optimal decisions with and without the regulation are contradictory, then firms may suspend investment in innovation until a policy uncertainty is reduced to a more comfortable level [1007].

Flexibility, the level of market information available and stringency all play significant roles in determining the impact of regulatory changes on innovation. Flexibility describes the number of implementation paths firms have available for compliance. Information describes whether a regulation promotes more or less complete information in the market. Stringency measures the degree to which a regulation requires compliance innovation and imposes a compliance burden on a firm, industry or market:

> Greater flexibility[114] and more complete information generally aid innovation; with stringency, there is a trade-off between the compliance burden and the type of innovation desired, as more radical innovation will generally come at a higher cost [1007].

'Fracking', the process of drilling for gas using high pressure water-chemical mixtures is an example of policy uncertainty affecting innovation in Australia. Different regulatory policies for fracking have been adopted in various Australian jurisdictions (e.g. Queensland, New South Wales and Victoria). For instance, the state of Victoria has banned alternative gas technologies, whereas the regulatory policy is unclear in NSW at present leading to significant uncertainty for investors and the community.

Similarly, the regulations for home-based photovoltaic power systems differ between states and change over time. Some states have mandatory feed-in tariffs that must be paid to consumers (e.g. Victoria and South Australia) while others leave any feed-in rate to the discretion of the relevant retailers (e.g. South east Queensland). The way that a feed-in tariff is paid (on a 'net' or 'gross' basis) differs between states. Further, the feed-in tariffs and the regulations surrounding them have changed over time, creating uncertainty for households who might invest in long-lived solar technology.

7.8.4 Incentives – motivate don't compel

An incentive is a motivation to act. There are government technological interventions that utilise incentives with better outcomes than 'command and control' regulation. Setting appropriate incentives for individuals and businesses can lead to desirable outcomes while limiting costs, and allowing flexibility for different technologies and approaches.

Well-known examples of the use of incentives as opposed to standard regulatory solutions include emission trading schemes. These schemes deal with the excessive emissions of certain types of pollution, such as carbon emissions or sulphur dioxide.

Incentives have also been used for technology changes in banking. In Australia, the Reserve Bank introduced 'direct customer charging' for automatic teller machines (ATM's). This regulation led to changes in consumer behaviour (by the choice to use ATMs), ATM operators (by creating incentives to provide new ATMs in innovative locations) and banks (by changing the size of their 'home' ATM networks). This relatively simple change to the way that pricing information was presented to customers, used incentives to alter the way that ATM technology was priced and deployed [565]. In contrast, the Reserve Bank used traditional 'command and control' regulation when dealing with interchange fees on credit card networks. This regulation has been modified on a number of occasions and further modifications have been suggested by the recent report of the Financial Systems Inquiry (see [204], recommendation 17). At best, this

---

[114] It has been shown that companies do not necessarily postpone investment decisions in the face of uncertainty if flexible regulation is in place:

> We trace this observation back to three motivations: securing competitive resources, leveraging complementary resources, and alleviating institutional pressure. We connect these motivations to fundamental principles of the resource-based view and institutional theory and further show the existence of a regime where institutionally motivated and resource-based actions are not necessarily decoupled. We base our research on a case study covering 80% of the German power generation industry which faces regulatory uncertainty from the European CO_2 Emission Trading Scheme [496].

traditional regulatory approach has only had modest success when compared to the incentives-based approach for ATM charging.

Care must be taken when using incentives. Incentive systems need to be robust and the results of using such systems can often not be predicted with certainty. For example, the Reserve bank's ATM reforms did not lead to direct price competition between ATMs. However, they did lead to the behavioural changes noted above. Overall, the changed incentives have improved choice for consumers, even though the price for using a 'foreign' ATM has not, in general, decreased.

Patents as incentives to improve local retention of skills and profits

Patent box is a tax regime for Intellectual Property revenues designed to encourage companies to make profits from their patents in a particular country by reducing the tax paid on those profits, thereby retaining skills in that country [492]. It aims to incentivise the commercialisation of patents by enabling companies to apply a lower rate of corporation tax to profits from patented inventions. The UK is currently implementing a patent box, which has been linked to enhancing the local economy by attracting investment from large corporations (e.g. GlaxoSmithKline plans to open a manufacturing plant in the UK for the first time in 40 years [899]). The Australian government is looking into an Australian Patent Box called the 'Australian Innovation and Manufacturing Incentive' (AIM), which seeks to keep innovation in Australia [45]. These schemes provide a reduced tax rate (typically between 5% and 15%) on income attributable to patented IP. The schemes have been well received and have proven to be effective at turning local innovation into local commercial realities [230].

Costing Mechanisms

As argued in Chapter 6 the cost of a technology is one of the principal determinants of adoption. Likewise, the cost of a regulatory intervention is central to its success. Beyond the simple question of what is the cost, there are creative means to share costs in a market driven manner that can lead to better technology choices.

Widespread deployment of energy storage technologies will rely heavily on cost. There is a great deal of support to allow demand and supply in the market to determine prices and diffusion. The International Energy Agency (IEA) recommends that governments avoid policies that mandate storage technologies and instead allow the market to drive uptake. However to create a market driven push, the IEA notes more work needs to be done on the lack of price transparency, high upfront investment costs and significant price distortions in current energy markets [516].

A report prepared by Energy Retailers Association of Australia (ERAA) outlines how retailers could lead a rollout of smart metering in Australia without the need for government intervention. Instead the scheme operates in a competitive market maintaining customer choice. Smart meters are a crucial component for an effective and efficient smart grid. The smart meter provides consumers and energy suppliers with up to date and accurate data on electricity usage. Instead of mandating a roll-out as Victoria has attempted to do, the Electricity Authority of New Zealand ensured there was open third party access to metering services and no barriers to competition or access to information. In this instance, the role of government is to ensure appropriate legislative and regulatory structures are in place to support the market driven rollout of smart meters by retailers. A market driven rollout will motivate consumers to have their meters upgraded in order to access better products. This means that the political risk to governments is greatly reduced relative to larger scale mandatory rollouts [334].

A spectrum auction is an innovative technology costing mechanism whereby a government uses an auction system to sell the rights to use specific frequency bands of the electromagnetic spectrum. With a well-designed auction, resources are allocated efficiently to the parties that value them the most, the government securing revenue in the process[115] [222]. In the past decade, telecommunications has turned into a highly competitive industry where companies are competing to buy valuable spectrum. This competition has been triggered by technological advancements, privatisation, and liberalisation [520]. Government incentives to purchase spectrum space had a downstream effect of encouraging industry innovation to maximise airwave use. Consequently, increased mobile industry providers creating innovative technologies led to increased consumer demand.

In addition, mechanisms can involve altering public behaviour by highlighting technology cost and use in innovative ways. Displaying neighbour electricity use on personal electricity bills has been shown to promote competition between neighbours, reducing electricity consumption [271].

7.8.5 Summary

- New technology does not necessarily require new regulation. Existing regulations can often adapt to new technology and this is easier when the regulation is focussed upon the underlying problem.
- Regulation should mostly focus on the desired outcome and the effects of using a technology, and not the technology itself.
- In some cases incentive based schemes may be preferable rather than 'command and control' regulation.
- Regulatory uncertainty can impede the development and commercialisation of technology.

7.9 Government investment in technological research and development

The returns to early stage Research and Development (R&D) are not easily appropriable to private players. National government investment in technological R&D can facilitate technological change.

Differences between countries in the set-up and nature of national institutions, in particular university education and the public research infrastructure, seems to be able to explain to a large extent differences between countries in innovation strength.
– Luc Soete [979]

No nation can 'free-ride' on the world scientific system. In order to participate in the system, a nation or indeed a region or firm needs the capability to understand the knowledge produced by others and that understanding can only be developed through performing research.
– Ammon J. Salter and Ben R. Martin [928]

There is now strong empirical evidence that while firms do value the results of scientific research they are less willing to invest in the fundamental research themselves. In the past 30 years there has been a steady decline in large firm direct investment in longer-term research and development[116] [32]. As a consequence, national governments sponsor research and

[115] The UK government raised £22.5 billion from an auction of five licences for radio spectrum to support the 3G mobile telephony standard in 2000 [120].
[116] The phrase 'longer-term' is used in preference to 'basic', 'applied', and 'strategic' because the key point regarding appropriability is time-scale, not the precise nature of the research. In any case, the distinctions are questionable; a better categorization is Stokes' quadrant based one, which categorises research according to whether it seels to solve problems of use, or problems of understanding, or both (the latter being 'Pasteur's quadrant') [1010].

development to obtain national benefit. The particular details of the impacts within Australia are the entire focus of an earlier Securing Australia's Future report [97] [327], which corroborates the finding that (in Australia) 'there are significant spillovers to productivity from public sector R&D spending on research agencies and higher education' [327]. However the report also found 'no evidence ... for productivity spillovers from indirect public support for the business enterprise sector, civil sector or defence R&D'. This needs careful interpretation since given the extremely low level (the lowest in the OECD – see [787], page 127) of firms in Australia collaborating on innovation with higher education or public research institutions, normal routes for spillover benefits seen in other countries are largely absent in Australia.

Advanced countries around the world recognise[117] the imperative of long term R&D funding for economic growth. In the UK, the Royal Society recommends that the UK 'put science and innovation at the heart of a strategy for long-term economic growth'; 'Cuts to science and innovation spending are a false economy', says the report. 'Science and innovation are investments that are central to short-term economic recovery and, more importantly, to long-term prosperity and growth' [918]. Australia does substantially invest in R&D[118] but has reduced this investment. By contrast, the UK protected the state science budget in its response to the global financial crisis [415].

The returns of early stage technology research and development are not readily appropriable by the people or institutions that conduct it[119]:

> It has been recognized by economists at least since the publication of Richard Nelson's now classic article [754], that "basic research generates substantial positive external economies. Private profit opportunities alone are not likely to draw as large a quantity of resources into basic research as is socially desirable". It is only since the early 1990s, however, that evidence has accumulated that the private sector also lacks the incentives to invest optimal amounts in applied research—particularly "early stage" applied research and technology development [924].

It is important to Australia that it derive economic returns on research and development; but that does not imply the returns need to be appropriated by the particular institution where the R&D was carried out. Much cannot be appropriated by the institution that conducted the research, but the country benefits all the same [610]. Top research universities in the US (where commercialisation is generally considered easier than Australia) only derive a small fraction of their income from licencing. The majority of universities do not even obtain sufficient commercial returns to cover the costs of operating their IP licencing offices [149,1084].

[117] According to Benoit Godin's comprehensive history of the idea of innovation, the notion that without government funding there will be inadequate investment in R&D, and that this will have deleterious social consequences, dates to the OECD in the early 1960s [431] (page 256.). The point is now widely accepted. What is contested is what are the best schemes and means to achieve the desired outcomes. Godin also stresses the importance of *technological* innovation, and explains its distinction to (but dependence upon) scientific research.

[118] Approximately 80% of industrial R&D spending centres on incremental improvement in existing product and process innovation because this is where profits can be realised quickly [504]. In 2011–12 Australian businesses invested 62% of their R&D expenditure in experimental development (using existing knowledge to create or improve products), and 32% in applied research (acquiring new knowledge with a specific application in view). Only 1% of business R&D spending went into research undertaken to acquire new knowledge without looking for long term benefits – so-called 'pure basic research' [5]. See the detailed figures in [285].

[119] See the vast literature on the topic [298,460,597,727,751,928,1032]. Appropriating the outputs of research by research institutions is difficult, complex and often fails [254].

The remainder of this section considers three factors associated with government investment in technological R&D that can facilitate the development and adoption of new technologies.

7.9.1 Reward success

A particular challenge for government support of technological R&D is when an institution shows signs of success - some will argue that therefore government support should be removed. This has occurred in the US where the Advanced Technology Program was cancelled because of its success. In Australia there is an expectation that the national research institute in ICT (National ICT Australia) should be self-funding [567,1063]. If an institution could easily derive a profit from early-stage research, then 'for-profit' companies would do it and government support would not be needed.

Like other interventions, sponsorship of R&D can be improved by using an experimental approach [62]. Policies should be viewed as experiments that aim to reduce uncertainty. The traditional approach does not do this.

> The problem is that much innovation policy remains rooted in industry policy, and has inherited many of its presumptions: such as a focus on planning, targets and sectoral programmes [62].
>
> The freedom to conduct experiments is essential to any society that has a serious commitment to technological innovation or to improved productive efficiency [912] (page 288).
>
> The key is to do *proper* experiments – an 'approach to innovation (and industrial) policy, involves search, experimentation, monitoring, learning and adaptation, all of which need to occur in a context of international openness to knowledge, trade, investment and competition' [316].

7.9.2 Acknowledge the challenge of appropriating returns in the design of institutions

Within Australia, many research institutions are driven by a perceived need to not only generate commercial returns, but to appropriate the benefits for themselves. Lessons from overseas corroborates this is counterproductive:

> Together, there is an increasing perception also *among business firms* that 'too much appropriability' hurts firms themselves. In fact, as noted by Florida "[l]arge firms are most upset that even though they fund research up front, universities and their lawyers are forcing them into unfavorable negotiations over intellectual property when something of value emerges. Angered executives at a number of companies are taking the position that they will not fund research at universities that are too aggressive on intellectual property issues. . . One corporate vice president for industrial R&D recently summed up the sentiment of large companies, saying, "The university takes this money, then guts the relationship". [But also] [s]maller companies are concerned about the time delays in getting research results, which occur because of protracted negotiations by university technology-transfer offices or attorneys over intellectual property rights. The deliberations slow the process of getting new technology to highly competitive markets, where success rests on commercializing innovations and products as soon as possible [300].

There are some institutions that have implemented more successful models with a more relaxed attitude to appropriability. The University of Waterloo in Canada famously relaxed its rules regarding intellectual property to allow it to vest automatically with the creators [135,506]. A consequence was the burgeoning of an economically successful industry cluster around the university. The experience of two outstanding universities in the UK also provides a useful example: Oxford and Cambridge have both set up science parks. The Cambridge Park flourishes; the Oxford one does not. Cambridge used a model assigning ownership of IP to the staff that developed it, whereas Oxford has adopted a policy similar to many other universities of having the IP owned by the university.

In 2005 Cambridge changed the rules to have the university automatically acquire certain rights, but it is clear[120] that that the inventors still derive a large benefit. It is not the exact model or percentages, but the *intent* and the *spirit.* Would the institution prefer a small percentage of a large economic success, or a large percentage of a small one? Institutions that seek to unduly control and appropriate the commercial proceeds flowing from research simply reduce the size of the pie, and reduce the incentive of researchers to take their research to the market.

Within Australia, NICTA, which operated with the objective of generating wealth for the country rather than appropriating it for itself, achieved a performance of 20 times the national average in number of start-ups created per federal research dollar [1134], arguably in large part due to not aiming to appropriate the returns to the institution.

Governments are encouraged to avoid tight appropriation by research institutions of the economic returns to R&D and instead encourage more R&D:

> Push back the boundaries between public or 'open' research and appropriable research. One often forgets that appropriability is socially justified only in so far it provides an incentive to innovation itself [300].

A recent report from the US National Academies gave as their first recommendation:

> The first goal of university technology transfer involving IP is the expeditious and wide dissemination of university-generated technology for the public good [679][121].

Open societies have enormous benefits in general [844], and open knowledge generation in technological R&D aids the free flow between public and private sectors which is beneficial [580].

Empowering the inventors is crucial in order to inspire them to take the plunge of taking their research to market, [679] (page 64). Recognising that perhaps the major long term pathway for impact is the training of graduate students within research institutions – a research institution that is not full of graduate students loses the best long term conduit of knowledge into the economy:

---

[120] See rule 25, page 29 of Chapter XIII [1074]. If Cambridge academics do not use the in house commercialisation organisation, then they are entitled to almost all of the commercial benefits. The point of offering such a majority share of the benefits to the inventor is not really about simple monetary incentive – it comes back to *autonomy and control*, which top researchers value enormously.

[121] The same report [679] clearly stated the complex pathways such transfer occurs:
The transition of knowledge into practice takes place through a variety of mechanisms, including but not limited to

1. Movement of highly skilled students (with technical and business skills) from training to private and public employment;
2. Publication of research results in the open academic literature that is read by scientists, engineers, and researchers in all sectors;
3. Personal interaction between creators and users of new knowledge (e.g., through professional meetings, conferences, seminars, industrial liaison programs, and other venues);
4. Firm-sponsored (contract) research projects involving firm- institution agreements;
5. Multifirm arrangements such as university-industry cooperative research centers;
6. Personal individual faculty and student consulting arrangements with individual private firms;
7. Entrepreneurial activity of faculty and students occurring outside the university without involving university-owned intellectual property; and
8. Licensing of IP to established firms or to new start-up companies.

> Skilled graduates who enter industry are a major channel through which basic research is transformed into economic benefit. … policies must ensure that basic research is closely integrated with the training of graduate students, with the latter carried out in organisations at the forefront of their field [928].

Finally, merely making IP and people more mobile is not enough – there needs to be the sort of vibrant ecosystem of business with the receptive capacity to exploit the results and talent. This issue is complex [597] and is not dealt with further in this report; there are many examples of success (Silicon Valley, Boston, Israel), but the causal reasons for their success are uncertain. Like all other interventions considered in this chapter, an experimental pluralistic approach with a broad holistic perspective would seem the best bet in the face of uncertainty.

7.9.3 Focusing technological R&D

Technology innovation is sometimes described using the market-demand (pull) and technology-push model, see Section 2.2. The market, by definition, looks after the demand-pull; thus public funding is warranted for the technology-push perspective. While the new knowledge that arises in the push model is valuable, it is not possible to foresee how the value can be captured specifically in advance, and so markets may under-invest in it.

The Australian Government's current innovation agenda was developed by looking at 'those industries that were already excelling in terms of trade performance' [475]. Maintaining competitiveness in these industry sectors is of course critical, and this requires improving their efficiency and productivity through the effective application of technology and innovation. This applies to incremental improvements derived from advanced algorithms and systems, through to transformative changes that change underlying value chains and hence business models. The research itself is performed in the ICT, materials or other technology sectors but it is applied in mining, transport, or other major industry sectors that underpin the economy.

The major problem with using existing industry sectors as a way of focussing technology research effort is that existing sectors are a poor guide for future large-scale industry developments. This is especially true regarding the fundamental transformations, which create entirely new industries (see Chapter 3):

> Imagine in the future that there will be a new sector built around a technology that we cannot yet anticipate (think of television or even the BBC from the standpoint of the mid-19th century before Maxwell, when science did not know that light was electromagnetic, let alone that such things as radio waves could exist). It is clearly not meaningful to assess whether this sector is a potential driver of growth, whether there are skill shortages or research opportunities awaiting public investment in the face of market failure, whether it is of strategic significance to the future of the nation or at risk from competition from China. But it is equally unsustainable to argue that the market can discover this missing knowledge; we simply do not know if the knowledge is there to be discovered [62].

Even 'neutral' industry policy can favour incumbent industries at the expense of new entrants:

> Governments who insist on neutrality with respect to new industries are bound to keep favoring the existing actors. For structural change, policy must be implemented to counter neutrality and to provide new industries with proper growth conditions [700].

Actively supporting new technologies instead of incumbents is a valuable strategy for a company aiming to survive and prosper. It is also a sound strategy for governments; see Appendix C.2 [930].

A further problem with a sectoral approach is that technological innovation does not respect industry sectoral boundaries. There is a very complex web of 'technological interdependence.' [906,908]. History shows that industry sectors do not transform themselves – radical innovation tends to come from the outside [533].

Technological innovation occurs by a process of invasion or colonisation: the flow of ideas, products, and processes from one sector, industry or firm to another. This illustrates the need for an alignment between the foci of government support and industries able to ultimately appropriate the benefits (otherwise there will be no opportunity for knowledge flow). This is an argument in favour of a better alignment between the size of various sectors and the expenditure of public research funds[122] [855]. Such an alignment would improve the 'absorptive capacity', that is the ability of existing industry to assimilate a new technology. Absorptive capacity is heavily dependent upon skills, which are themselves a by-product of government R&D sponsorship [538].

Advances in underpinning general purpose technologies not only aid existing industries, they create new ones:

> A missing element in the assessment of the social returns to publicly funded R&D conducted at universities, federal research labs, and other nonprofit/public institutions is the role that public R&D plays in the creation of new industries, [619] (page 105).

This illustrates the slipperiness of the boundary between invention, adoption, adaptation (modifying a technology developed for a given problem), exaptation (adopting a technology developed for a given problem to a new problem) [280]. It is often claimed that 'Australia performs strongly on research excellence, but we perform poorly by international standards in translating publicly funded research into commercial outcomes.' ([269], page 3). The skills needed for adoption, adaptation, exaptation, invention and commercialisation have much in common, and it is not obvious these distinctions are helpful – is using machine learning technology (developed elsewhere) in a completely novel manner to predict water pipe failures [766] adoption, adaptation, exaptation, invention or commercialisation?

The technologies that have had, and are likely to continue to have, the largest economic impact are general-purpose technologies [138,382,482,823]. The very point of general-purpose technologies is that they can have transformative impact across *all* industry sectors. This transformation occurs via recombinant innovation – the combination of ideas leading to radically new products and services:

> Countries best able to master recombinant dynamics have proven able to achieve more rapid increase of their multifactor productivity growth [29].

---

[122] The report cited argues

> The disconnection between the research agendas of industry and the university sector is acute. In 2010, businesses spent 52 per cent of their R&D outlay on engineering and 28 per cent on ICT. Correspondingly, universities spent 9 per cent on engineering and only 4 per cent on ICT. On the other hand, while universities spent 38 per cent of their research expenditure on medical and health sciences and biological sciences, the comparable figure for business is 6 per cent, [855] (page 8.).

Of course there are other reasons for public support of research, and disciplines like (for example) pure mathematics or astronomy have compelling reasons in their own right to be substantially supported (being two of the most profound human pursuits imaginable). Furthermore, since these disciplines push forward the boundaries of knowledge, one can be certain that in due course they will lead to economic benefit in the same way they have in the past – number theory (perhaps the purest part of pure mathematics) underpins global electronic commerce through its foundations for cryptography [64]; within Australia, the development of the fast-Fourier transform chip (motivated by problems arising in astronomy) lead to the substantial role Australia played in the development of WiFi [654] – 'This was done in the broader national interest not for direct commercial gain by the organization [CSIRO]'[655] (page 25;); see especially annex C for the complex antecedents of the ultimate economic impact.

Government investment in technological R&D should be at the broad level of general-purpose technologies – arguably the underlying 'engines of economic growth' [622] [139]:

> An important inference of the theoretical literature on the development of general purpose technologies is that public investment in their development is necessary if economic growth is to be sustained. ... Public investment in the development of general purpose technologies is necessary to achieve an efficient allocation of research and development resources [924].

Consequently focusing government support of technology R&D at the level of general purpose technologies, especially ICT[123], is a valuable intervention.

> One of the most relevant policy issues is whether ICT can be defined as a GPT, which is a technology that stimulates co-inventions and product, process and organizational innovations. While the evidence gathered from industry-level data is not conclusive, the evidence from firm and plant- level data seem to point consistently to the presence of spillover and external effects generated by ICT capital (at the industry or aggregate level). The fact that these spillovers and externalities are found more easily with more granular data is consistent with the intuition that, at a lower level of aggregation, we are more likely to have external factors affecting firms' performance (in the limiting case of country-level data the spillovers can come only from outside the country). This means that there might be room for public polices supporting investment in ICT, and even more for policies supporting R&D in the ICT sector, as in this case we have two types of externalities, one related to ICT capital and the other one related to R&D capital [112] (page 62).

Australia does not need to do this in a manner that 'picks specific technology winners.' At an extreme level of aggregation, one is simply picking a general purpose technology which is a good bet[124]. However merely embracing (say) ICT is hardly picking a winner in the negative sense, because it is such a broad (and vague) category; indeed it would be foolhardy to *not* embrace ICT.

Australia would be well served by viewing its publicly funded R&D institutions as an entrepreneurial national asset – that is to be an 'entrepreneurial state' where Governments are not preoccupied about the difference between public and private sector, but work collaboratively and in an entrepreneurial spirit to better the fortunes of the country [662]. There are exemplars around the world that can serve as guidance, such as the development of Israel's semiconductor industry [603].

7.9.3 Summary

- Investment in early stage technology research facilitates its transmission and adoption into the community[125]. Government funded research institutions must invest in the training of graduate students.
- Technology R&D support should be focussed on technological areas, not existing industry sectors. To achieve advances in human health, government cannot just invest in the medical sector; to achieve advances in transport, government cannot just invest in roads. If large economic impact is desired, expect that the underpinning sources are derived from a very wide diversity of disciplines[126].

---

[123] ICT is particularly central because the significance of control and information to *all* aspects of life. This importance of ICT is not new – information and control have been central for centuries, [102] (pages 434-435.).
[124] See the discussion of State picking winners versus Losers picking the state in chapter 1 of [53].
[125] The US National Academy of Engineering has recently felt it necessary to urgently recommend a *doubling* of US federal R&D funding, already substantially higher per GDP than that in Australia [44]. This seems appropriate advice for Australia and the most obvious response to the question of how to boost the commercial returns to research [269].
[126] See the famous 'tyre-tracks' diagram in [742].

- Big wins will come from the further advance and adoption of general-purpose technologies, such as ICT, advanced materials, biotechnology, and nanotechnology [286].
- R&D (including the means by which it is organised and institutionalised) should be viewed as an experiment, and methods and institutions that succeed should be supported.
- Skills transfer via a pipeline of human talent is a vital transfer mechanism – see footnote 121.
- Sticking with what currently makes a profit is precisely the 'innovators dilemma' whereby large and successful companies fall prey to their own success because that cannot radically innovate [184]. Australia stands to fall prey to this well-known error if it continues to focus upon industries and technologies that have performed well in the past, rather than looking to the future.
- Patents and intellectual property rights are central to appropriating returns and government investment of early stage technological research and development[127].
- Understanding the means by which technological research is translated into use can help design better R&D support schemes [118]. This is complex because researchers' motivations are complex [935] and simple incentives can backfire, see Working paper: Performance based research funding – an overly simplistic technological intervention.

7.10 The complexity of technological intervention

The complexity of technology and technological change implies that any technological intervention is also complex. Conditions and potentially useful interventions favouring innovation and adoption of new technologies include:

1. Devolve where possible – no single person or organisation can hope to assimilate, assess or intervene on all aspects of technology.
2. Take an extrinsic approach to technological intervention – technologies are not *intrinsically* good or bad; their *use* is.
3. Transparency and open access to information help achieve better technological interventions.
4. Creativity and tinkering are essential skills to be inculcated into Australians; doing so will create a workforce more adaptable to and accepting of new technologies. Focussing education on such skills should complement, not replace, a strong and necessary enhancement in science and mathematics skills. More generally, education should focus on adaptability to technological change.

---

[127] However the vexed matter of how the substantial intervention of patent law might be adjusted or improved is very complex and will not be examined further in this report. A sample of the literature shows the complexity of the problem [110,111,124,378,419,442,447,457,462,566,677,702,719,720,892,951,1049,1080]. Tesla has made their patents freely available to improve R&D into electric vehicle technology with the aim of increasingly efficiency and market demand for electric vehicles. Tesla have made information openly available knowing one company cannot feasibly do all the R&D and it is putting an end product together well that improves market share [387].

> 'Tesla made a seemingly unusual move today: it invited competitors to use its patents, for free. In a post on the company's blog, CEO Elon Musk declared that Tesla's "true competition is not the small trickle of non-Tesla electric cars being produced, but rather the enormous flood of gasoline cars pouring out of the world's factories every day."
>
> Rather than worrying about car companies copying their technology, Tesla now hopes they will do so, in order to expand the overall market for electric vehicles. A Tesla vehicle is quite literally more valuable than the sum of the parts, even when the value of the patented technology is included. "They have this sexy car that people are increasingly liking," says Lobel. "It's something different from just the aggregation of the knowledge in the patents."

5. Technologies progress by learning from failure, and technological interventions can too. Much can be learned from entrepreneurs, scientists and technologists regarding how best to learn from failure.
6. Explicit experimentation is the best strategy to deal with the intrinsic uncertainty of new technology. Such experimentation is best done in small, independent groups.
7. Interoperability of technologies is central to the adoption of new technologies. Standards, platforms and gateway technologies can facilitate interoperability. Governments can (and should) encourage the setting of standards, but should not necessarily design the standards themselves.
8. Some emerging technologies require modifications to regulation, but it is typically better for regulation to focus upon the effects of using technology not the technological artefact/process itself. In many cases new regulations are not needed to deal with emerging technology. Incentives are often more effective at influencing behaviour surrounding new technologies than regulation.
9. The economic returns to early stage technological research and development are difficult to appropriate and this remains a compelling reason for long-term and substantial government support of technology R&D. Such support should reward, not punish, success and should be focussed on technological capability (especially general purpose technologies) rather than pre-existing industry sectors.

Conclusion – adapt or wither

Technology is complex and dynamic. Many of the qualities of a particular technology are not intrinsic to the technology, but are dependent upon many factors in the broader environment. Changes of the environment can substantially alter the value of the technology. Technologies and industries that have performed well in the past will not necessarily perform well in the future, at least without substantial adaptation and transformation (see the discussion of Fuji vs Kodak in Section 4.1). Whilst it is possible for companies to adapt to external disruption, they cannot do so by sticking with what has worked so far. Adaptation involves innovation, change, and new technologies. Governments that insist upon neutrality of interventions tend to favour entrenched incumbent industries, which are typically least able to adapt.

Australia's choice is analogous to that of a company relying on certain technologies, doing well at present, but waking up to the fact that the world keeps changing [183]. Sticking with what currently works (for example, coal as an export that is valuable because the world currently relies upon it as a primary source of energy) will not be as profitable when the broader environment changes (for example, alternative energy sources become cheaper). What seems valuable now, will not remain so. Acknowledging that the world is changing, and *embracing that change as a valuable business opportunity*, can lead to growth and prosperity. Such a strategy has been embraced by other high performing countries which are are 'prioritising their research and innovation support to gain competitive advantage for future growth areas such as green technologies and health and to help address global challenges' [788] (page 90).

Australian historian of technology Roy Macleod writing on the colonial history of Australian engineering observed:

> The myths of the 'bush engineer' assume a topical, if somewhat contradictory importance. Just as in the world wars - when 'colonial' and 'bush' qualities of versatility and ingenuity were required of Australian engineers mobilised overnight into intelligence, radar and aviation - so today, in a world of high technology, a *mentalité* that celebrates flexibility, innovativeness, and adaptability is essential [639].

Adaptability can be challenging. Courage and confidence is needed. Australian historian of technology Ann Moyal reflected on Australia's technological past as a guide to the present:

> Contemporary attitudes would undoubtedly benefit from an injection of pioneering confidence to reduce Australia's prevailing stance of risk-aversion [728].

Australia's prosperity lies upon shifting foundations. The foundations have shifted before and are shifting now. Australian economic historian Ian McLean concluded his book *Why Australia Prospered: The shifting sources of economic growth* by observing that

> Australia has experienced both brief and prolonged periods of resource-based prosperity in the past; adjusting to their demise has invariably being wrenching. At the same time, [there is an] appreciation of the potential threat to longer-run prosperity posed by the current resource boom, and of the continuing [need] to creatively engage in the institutional innovation required to sustainably manage it…. Perhaps these are examples of Australians learning from their past [670].

The lesson that needs to be learned is not unique to Australia [1027] but it is especially important here given our natural resource dependence. The transformations wrought by technological revolutions in the past have unleashed subsequent Golden Ages, but only when new technologies were embraced [825].

Australia needs to *adapt* to the shifting foundations. It needs to change its strategy from focusing upon what worked well in the past, or business sectors that have been demonstrated to have strengths in the past. Instead Australia should create and sustain the capacity, skills, culture and the will to adopt, adapt, and develop its future source of prosperity and well-being: Australia's bright future can be envisaged, created and achieved through new technology.

References

A [bibliographer] would be a more useful fellow …
if he could practise deletion and bring into
existence an accredited *Index Expurgatorius*
– John Maynard Keynes, *A Treatise on Probability,* 1921

The bibliography on the following pages lists all works cited in the report, comprising less than half of those examined during the project. Taking Keynes' above advice, below we have created our own *Index Expurgatorius* – not forbidden books, but rather selected and recommended ones: works most appropriate for a reader interested in better understanding technological change in general. The following 30 works are our recommendations.

1. Patrick Kelly, Melvin Kranzberg, Frederick A. Rossini, Norman R. Baker, Fred A. Tarpley, Jr and Morris Mitzner, *Technological Innovation: A Critical Review of Current Knowledge* (Volume 1, *The Ecology of Innovation* and Volume 2, *Aspects of Technological Innovation*), Advanced Technology and Science Studies Group, Georgia Tech, Atlanta, Georgia, (February 1975)
2. Chris Freeman and Francisco Louçã, *As Time Goes By: From the Industrial Revolutions to the Information Revolution*, Oxford University Press, (2001)
3. Richard G. Lipsey, Kenneth I. Carlaw, and Clifford T. Bekar, *Economic Transformations: General Purpose Technologies and Long-term Economic Growth*, Oxford University Press, (2005)
4. Richard R. Nelson, *Technology, Institutions, and Economic Growth,* Harvard University Press, (2005)
5. George Basalla, *The Evolution of Technology,* Cambridge, Cambridge University Press, (1988)
6. Giovanni Dosi, Technological Paradigms and Technological Trajectories. *Research Policy,* 11**,** 147-162, (1982)
7. Seabury Collum Gilfillan, The prediction of technical change. *Review of Economics and Statistics*, 34(4), 368-385, (1952)
8. David S. Landes, *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present*: Cambridge University Press, (2003)
9. Thomas P. Hughes, *Human Built World: How to think about technology and culture*, University of Chicago Press, (2004)
10. W. Brian Arthur, *The Nature of Technology: What it is and How it Evolves*, Free Press, (2009)
11. Arnold Pacey, *Meaning in Technology*, MIT Press, (1999)
12. Arnold Pacey, *The Culture of Technology*, MIT Press, (1983)
13. Nathan Rosenberg and L.E. Birdzell, Jr, *How the West Grew Rich: The Economic Transformation of the Industrial World*, Basic Books, (1986)
14. Donald MacKenzie and Judy Wajcman*, The Social Shaping of Technology*, Open University Press, (1999)
15. Wiebe E. Bijker, Thomas P. Hughes and Trevor Pinch, *The Social Construction of Technological Systems*, MIT Press (1987).
16. Nathan Rosenberg, *Inside the Black Box: Technology and Economics*, Cambridge University Press, (1982)
17. James R. Beninger, *The Control Revolution: Technological and Economic Origins of the Information Society*, Harvard University Press, (1989)
18. Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress*, Oxford University Press, (1990)
19. Joel Mokyr, *The Gifts of Athena: Historical Origins of the Knowledge Economy,* Princeton University Press, (2002)
20. Robert D. Atkinson and Stephen J. Ezell, *Innovation Economics: The Race for Global Advantage*, Yale University Press, (2012)
21. David Edgerton, *The Shock of the Old: Technology and Global History since 1900*, Oxford University Press, (2007)
22. Ralph Landau and Nathan Rosenberg (Eds), *The Positive Sum Strategy: Harnessing Technology for Economic Growth,* National Academies Press, (1986)
23. Everett M. Rogers, *Diffusion of Innovations,* Free Press, (2003)
24. Vernon W. Ruttan, *Technology, Growth and Development: An Induced Innovation Perspective,* Oxford University Press, (2001)
25. Paul A. David, Clio and the economics of QWERTY, *The American Economic Review*, 75(2), 332-337, (May 1985)
26. John Jewkes, David Sawers and Richard Stillerman*, The Sources of Invention*, St Martins Press, (1959)
27. John Ziman, *Technological Innovation as an Evolutionary Process*, Cambridge University Press, (2000)
28. Stewart Brand, *How Buildings Learn: What Happens After they are Built*, Penguin Books, (1994)
29. Frank W. Geels, *Technological Transitions and System Innovations: A co-evolutionary and Socio-Technical Analysis*, Edward Elgar, Cheltenham, (2005).
30. Kim Stanley Robinson, *The Mars Trilogy*, Random House, (1993-6) (A novel admirably depicting the technologist's experience of technology, and the source of the apposite inspirational neologism 'monocausotaxophilia' which inspired the pluralistic approach of the report.)

[1] Proceedings of the 2nd International Workshop on Mining Urban Data co-located with 32nd International Conference on Machine Learning (ICML 2015). In: Ioannis Katakis, Francois Schnitzler, Dimitrios Gunopulos, Katharina Morik, Gennady Andrienko et al., editors., MUD 2015 Mining Urban Data; Lille, http://ceur-ws.org/Vol-1392/MUD22015-complete.pdf

[2] Scott Aaronson, The limits of quantum. *Scientific American*, 29862-69, (2008)

[3] Pekka Abrahamsson, Outi Salo, Jussi Ronkainen, Juhani Warsta, *Agile software development methods: review and analysis*. Espoo: VTT Technical Research Centre of Finland, (2002)

[4] ABS, *In Focus: Crime and Justice Statistics, July 2012 (4524.0)*, January 2015, http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/4524.0Chapter200July 2012

[5] ABS, *Research and Experimental Development, Businesses, Australia, 2011-12*, 22 March 2015, http://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/8104.0Main features22011-12

[6] ABS, *Counts of Australian Businesses, including Entries and Exits, June 2008 to June 2012*, http://www.abs.gov.au/ausstats/abs@.nsf/Previousproducts/8165.0Main Features3Jun 2008 to Jun 2012?opendocument&tabname=Summary&prodno=8165.0&issue=Jun 2008 to Jun 2012&num=&view, 2014

[7] ABS, *Innovation in Australian Business: Novelty*, http://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/8158.0Main Features92012-13?opendocument&tabname=Summary&prodno=8158.0&issue=2012-13&num=&view, 2014

[8] ABS, *Causes of Death, Australia, 2013*, http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by Subject/3303.0~2013~Main Features~Leading Causes of Death~10001

[9] Evan Ackerman, Inside the Dynomak: A Fusion Technology Cheaper than Coal. *IEEE Spectrum*, (2014) http://spectrum.ieee.org/energy/nuclear/inside-the-dynomak-a-fusion-technology-cheaper-than-coal

[10] ACMA, *Australia in the Digital Economy: Report 2 Online Participation*. Canberra: Commonwealth of Australia, (2009)

[11] Laird Addis, Monistic Theories of Society. *Proceedings of the Biennial Meeting of The Philosophy of Science Association*: Springer. pp. 209-216 (1974)

[12] Gediminas Adomavicius, Jesse C. Bockstedt, Alok Gupta, Robert J. Kauffman Technology roles in an ecosystem model of technology evolution. Carlson Scool of Management, University of Minnesota, (2005)

[13] Mamoun Alazab, Roderic Broadhurst, Spam and Criminal Activity. *Trends and Issues (Australian Institute of Criminology) Forthcoming*, (2014)

[14] Jacob Albert, *Interoperability case study: intermodal containers and global cargo transport*. Harvard University, (2012) http://cyber.law.harvard.edu/publications

[15] Christopher Alexander, *Notes on the synthesis of form*. Cambridge MA: Harvard University Press. (1964)

[16] Christopher Alexander A city is not a tree. Design. London: Council of Industrial Design, (1966)

[17] Christopher Alexander, The role of the Architect in the Third Millennium. *The Nature of the Order: An Essay on the Art of Building and the Nature of the Universe Book Two The Process of Creating Life*. Berkeley: The Center for Environmental Structure. pp. 551-564 (2002)

[18] Hunt Allcott, Sendhil Mullainathan, Dmitry Taubinsky, *Externalizing the internality*. New York University Working Paper, (2011)

[19] L Allen, MW Beijersbergen, RJC Spreeuw, JP Woerdman, Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes. *Physical Review A*, 45:11 8185-8189, (1992)

[20] Teresa Amabile, Steve Kramer, What doesn't motivate creativity can kill it, 25 April 2012, https://hbr.org/2012/04/balancing-the-four-factors-tha-1/https://hbr.org/2012/04/balancing-the-four-factors-tha-1/

[21] Robert H Ament, Comparison of Delphi forecasting studies in 1964 and 1969. *Futures*, 2:1 35-44, (1970)

[22] American Heart Association, *180,000 deaths worldwide may be associated with sugary soft drinks*, http://newsroom.heart.org/news/180-000-deaths-worldwide-may-be-associated-with-sugary-soft-drinks

[23] Johnson Amoako, Anthony Ockwell, Madhumita Lodh. The economic consequences of the health effects of transport emissions in Australian capital cities. 26th Australasian Transport Research Forum; Wellington, New Zealand, http://www.atrf.info/papers/2003/2003_Amoako_Ockwell_Lodh.pdf

[24] James M. Anderson, Nidhi Kalra, Karlyn D. Stanley, Paul Sorensen, Constantine Samaras, et al., *Autonomous Vehicle Technology: A guide for policymakers*. RAND, (2014)

[25] Ross Anderson, Chris Barton, Rainer Böhme, Richard Clayton, Michel JG Van Eeten, et al., Measuring the cost of cybercrime. *The economics of information security and privacy*: Springer. pp. 265-300 (2013)

[26] David L Andrews, Mohamed Babiker, editors *The angular momentum of light*. Cambridge: Cambridge University Press. (2013)

[27] Cristiano Antonelli, *The Microdynamics of Technological Change*. London: Routledge. (1999)

[28] Cristiano Antonelli, *Handbook on the Economic Complexity of Technological Change*. UK: Edward Elgar Publishing. (2011)

[29] Cristiano Antonelli, Jackie Krafft, Francesco Quatraro, Recombinant knowledge and growth: The case of ICTs. *Structural Change and Economic Dynamics*, 21:1 50-69, (2010)

[30] Daniele Archibugi, Mario Pianta, Measuring technological change through patents and innovation surveys. *Technovation*, 16:9 451-468, (1996)

[31] Linda Argote, Dennis Epple, Learning Curves in Manufacturing. *Science*, 247920-924, (1990)

[32] Ashish Arora, Sharon Belenzon, Andrea Patacconi, *Killing the golden goose? The decline of science in corporate R&D*. Cambridge MA: National Bureau of Economic Research, (2015) http://www.nber.org/papers/w20902

[33] Ashish Arora, Alfonso Gambardella, *From underdogs to tigers: the rise and growth of the software industry in Brazil, China, India, Ireland, and Israel*. Oxford: Oxford University Press. (2006)

[34] W Brian Arthur, Competing technologies, increasing returns, and lock-in by historical events. *The economic journal*, 99:394 116-131, (1989)

[35] W Brian Arthur, The structure of invention. *Research Policy*, 36:2 274-287, (2007)

[36] W Brian Arthur, *The nature of technology: What it is and how it evolves*: Free Press. (2009)

[37] Peter Asaro, On banning autonomous weapon systems: human rights, automation, and the dehumanization of lethal decision-making. *International Review of the Red Cross*, 94:886 687-709, (2012)

[38] Madeline Ashby, Karl Schroeder, Kathleen Maher, Rob Enderle, John Peddie, et al., *Imagining the future and building it*: Intel Corporation. (2012)

[39] Nicholas A Ashford, George R Heaton, Regulation and technological innovation in the chemical industry. *Law and Contemporary Problems*, 46:3 109-157, (1983)

[40] Isaac Asimov Visit to the World's Fair of 2014. New York Times (Review of Books), (1964) http://www.nytimes.com/books/97/03/23/lifetimes/asi-v-fair.html

[41] World Nuclear Association, *Nuclear Regulation and Regulators*, 21 July 2015, http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Appendices/Nuclear-regulation---regulators/

[42] Thomas Åstebro, Holger Herz, Ramana Nanda, Roberto A Weber, Seeking the roots of entrepreneurship: insights from behavioral economics. *Journal of Economic Perspectives*, 28:3 49–70, (2014)

[43] Robert D. Atkinson Book review of Choosing a future: the second machine age by Erik Brynjolfsson and Andrew McAfee. Issues in Science and Technology. New York. pp. 90-92, (2014)

[44] Norman R Augustine, C Barrett, G Cassell, N Grasmick, C Holliday, et al., *Rising above the gathering storm, revisited: Rapidly approaching category 5*. Washington, DC: National Academy of Sciences, National Academy of Engineering, Institute of Medicine, (2010)

[45] AusBiotech Policy position for further tax reform: Australian Innovation & Manufacturing (AIM) Incentive. http://www.ausbiotech.org/userfiles/file/AIM_AusBiotech_April_2014.pdf

[46] Australian Academy of Science, *From stump-jump plough to interscan: a review of invention and innovation in Australia*. Canberra: Australian Academy of Science, (1977)

[47] Australian Academy of Technological Sciences and Engineering (ATSE), *Technology in Australia 1788-1988*. Melbourne: Australian Academy of Technological Sciences and Engineering. (1988)

[48] Australian Geographic Shark attacks in Australia: a timeline. Australian Geographic, (2015) http://www.australiangeographic.com.au/topics/science-environment/2015/02/shark-attacks-in-australia-a-timeline

[49] Australian Industry Group, *Technology Investment and Productivity in Australian businesses: Ready or Not?* , (2013)

[50] Australian Pesticides and Veterinary Medicines Authority, *Regulatory Considerations for Nanopesticides and Veterinary Nanomedicines: A Draft*. ACT: Commonwealth of Australia, (2014) http://apvma.gov.au/sites/default/files/docs/report-draft-regulatory-considerations-nanopesticides-veterinary-nanomedicines.pdf

[51] Australian Public Service Commission, *Changing Behaviour: A public policy perspective*. Canberra: Commonwealth of Australia, (2007)

[52] Australian Science and Technology Council (ASTEC), *Technological change and employment*. Canberra: Australian Government, (1983)

[53] Technology and Engineering Council (ASTEC) Australian Science, *Developing long-term strategies for science and technology in Australia - findings of the study: matching science and technology to future needs 2010*. Canberra: Australian Science, Technology and Engineering Council, (1996)

[54] Technology and Engineering Council (ASTEC) Australian Science, *Developing long-term strategies for science and technology in Australia: outcomes of the study matching science and technology to future needs: 2010*. Canberra: Australian Science, Technology and Engineering Council, (1996)

[55] Technology and Engineering Council (ASTEC) Australian Science, *Foundations for Australia's future: science and technology in primary schools*. Canberra: Australian Science, Technology and Engineering Council (ASTEC), (1997)

[56] Australian Venture Consultants Pty Ltd, *Rise of the Machines?* : Resources Industry Training Council, (2012)

[57] Ryan Avent, Tragedies of the commons: the world is his parking spot, 9 March 2011, http://www.economist.com/blogs/freeexchange/2011/03/tragedies_commons

[58] Pierre Azoulay, Joshua S Graff Zivin, Gustavo Manso, Incentives and creativity: evidence from the academic life sciences. *RAND Journal of Economics*, 42:3 527-554, (2011)

[59] Raffaella Baccolini, Tom Moylan, editors *Dark horizons: science fiction and the dystopian imagination*. New York: Routledge. (2003)

[60] Emily Badger, What the steamship and the landline can tell us about the decline of the private car, 11 March 2013, http://www.citylab.com/tech/2013/03/what-steamship-and-landline-can-tell-us-about-decline-private-car/4930/

[61] Stacy Baird, The government at the standards bazaar. In: Laura DeNardis, editor. *Opening standards: the global politics of interoperability*. Cambridge MA: MIT Press. pp. 13-31 (2011)

[62] Hasan Bakhshi, Alan Freeman, Jason Potts, *State of uncertainty: innovation policy through experimentation*. London: NESTA, (2011)

[63] Margherita Balconi, Stefano Brusoni, Luigi Orsenigo, In defence of the linear model: An essay. *Research Policy*, 39:1 1-13, (2010)

[64] M.W. Baldoni, C. Cilliberto, G. M. Piacentini Cattaneo, *Elementary Number Theory, Cryptography and Codes*. Roma: Springer. (2009)

[65] Carliss Y Baldwin, Kim B Clark, *Between 'knowledge' and 'the economy': notes on the scientific study of designs*. Harvard Business School, (2005)

[66] Carliss Y Baldwin, Kim B Clark, Modularity in the design of complex engineering systems. In: Dan Braha, AA Minai, Yaneer Bar-Yam, editors. *Complex engineered systems*. Berlin: Springer. pp. 175-205 (2006)

[67] Carliss Young Baldwin, Kim B Clark, *Design rules: the power of modularity*. Cambridge MA: MIT Press. (2000)

[68] Gabriele Bammer, Michael Smithson, editors *Uncertainty and risk: multidisciplinary perspectives*. London: Earthscan. (2008)

[69] A Bandivadekar, K Bodek, L Cheah, C Evans, T Groode, et al., *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions*. Cambridge MA: Laboratory for Energy and the Environment, Massachusetts Institute of Technology, (2008) http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/

[70] D Banta, What is technology assessment? *International Journal of Technology Assessment in Health Care*, 257-9, (2009)

[71] Ofer Bar-Yose, The Natufian culture in the Levant, threshold to the origins of agriculture. *Evolutionary Anthropology*, 6:5 159-177, (1998)

[72] Michael S Baram, Technology assessment and social control. *Jurimetrics Journal*, 1479-99, (1973)

[73] Michael S. Baram, Cost-Benefit Analysis – An Inadequate Basis for Health, Safety, and Environmental Regulatory Decision Making. *Ecology Law Quarterly*, 8:473 473-531, (1979-1980)

[74] M Barber, K Donnelly, S Rizvi, *AN AVALANCHE IS COMING Higher education and the revolution ahead*. Institute for public policy research, (2013)

[75] David Barberá-Tomás, Davide Consoli, Whatever works: uncertainty and technological hybrids in medical innovation. *Technological Forecasting and Social Change*, 79:5 932-948, (2012)

[76] Graeme Barker, *The agricultural revolution in prehistory: why did foragers become farmers?* Oxford: Oxford University Press. (2006)

[77] Lachlan Barker, *Greg Hunt and the paid polluters' 'lower' electricity prices*, https://independentaustralia.net/environment/environment-display/greg-hunt-and-the-paid-polluters-electricity-prices,7048, 2014

[78] Lachlan Barker, Who's paying for the Abbott Government propaganda in our power bills, 19 September 2014, https://independentaustralia.net/environment/environment-display/whos-paying-for-the-abbott-governments-propaganda-in-our-power-bills,6913

[79] Thomas Barlow, *The Australian miracle: an innovative nation revisited*: Picador Australia. (2006)

[80] HG Barnett, *Innovation: the basis of cultural change*. New York: McGraw Hill. (1953)

[81] Ann Bartel, Frank R Lichtenberg, The Comparative Advantage of Educated Workers Implementing New Technology. *The Review of Economics and Statistics*, 69:1 1-11, (1987)

[82] George Basalla, *The evolution of technology*. Cambridge: Cambridge University Press. (1988)

[83] Bjørn L Basberg, Patents and the measurement of technological change: a survey of the literature. *Research Policy*, 16:2 131-141, (1987)

[84] Jr. Bassett, R David, John Pucher, Ralph Buehler, Thompson, et al., Walking, cycling, and obesity rates in Europe, North America, and Australia. *Journal of Physical Activity and Health*, 5:6 795-814, (2008)

[85] Philippe Baumard, William H Starbuck, Learning from failures: why it may not happen. *Long Range Planning*, 38281-298, (2005)

[86] BBC, *3D sport channel on ESPN to close after three years*, http://www.bbc.co.uk/news/entertainment-arts-22886822, 2013

[87] BBC 3D sport channel on ESPN to close after three years. (2013) http://www.bbc.co.uk/news/entertainment-arts-22886822

[88] BBC, *BBC 3D programming 'on hold' indefinitely*, http://www.bbc.com/news/entertainment-arts-23195479, 2013

[89] BBC BBC 3D programming 'on hold' indefinitely. (2013) http://www.bbc.co.uk/news/entertainment-arts-23195479

[90] BBC, US spy chief James Clapper highlights cyber threats, 27 February 2015, http://www.bbc.com/news/world-us-canada-31654050

[91] Kent Beck, Mike Beedle, Arie Bennekum, Alistair Cockburn, Ward Cunningham, et al., *Manifesto for Agile Software Development*, http://agilemanifesto.org/

[92] Matthew J. Beck Sunday drive: Review of automobile ownership, societal and environmental impacts and behavioural change. University of Sydney: Institute of Transport and Logistics Studies, (2013) http://sydney.edu.au/business/itls/research/publications/working_papers/2013

[93] Matthew B Becker, *Interoperability case study: THE BAR CODE/UPC*. Cambridge MA: Berkman Center for Internet & Society, Harvard University, (2012) http://ssrn.com/abstract=2031107

[94] Burnham P Beckwith, *Ideas about the future: a history of futurism, 1794-1982*. Palo Alto: Burnham Putnam Beckwith. (1986)

[95] Sharon Begley, *Insight: America's hatred of fat hurts obesity fight*, http://www.reuters.com/article/2012/05/11/us-obesity-stigma-idUSBRE84A0PA20120511, 2012

[96] Daniel Bell, The world and the United States in 2013. *Daedalus*, 116:3 1-31, (1987)

[97] J Bell, B Frater, L Butterfield, S Cunnigham, M Dodgson, et al., *The role of science, research and technology in lifting Australian productivity*. Australian Council of Learned Academies, (2014) http://www.acola.org.au/PDF/SAF04Reports/SAF04 Role of SRT in lifting Aus Productivity FINAL REPORT.pdf

[98] Thomas Bell, May 24th, 1859: Anniversary meeting. *Proceedings of the Linnean Society of London*, IVviii-ixff, (1860)

[99] Edward Bellamy, *Looking backward: from 2000 to 1887*. Boston: Houghton Mifflin. (1888)

[100] Arden Jr Bement, Debasish Dutta, Lalit Patil, *Educate to innovate: factors that influence innovation*: National Academies Press. (2015)

[101] Gregory Benford, *The wonderful future that never was: flying cars, mail delivery by parachute, and other predictions from the past*: Hearst. (2012)

[102] James R Beninger, The control revolution. *Technological and economic origins of information society Cambridge*, (1986)

[103] Warren Bennis, *On becoming a leader*. Philadelphia PA: Basic Books. (2009)

[104] Michael L Berger, *The automobile in American history and culture: A reference guide*. Westport Conneticut: Greenwood Publishing Group. (2001)

[105] Frans Berkhout, Julia Hertin, *Impacts of information and communication technology on environmental sustainability: speculations and evidence. Report to the OECD*. Brighton UK: University of Sussex, (2001) http://www.oecd.org/sti/inno/1897156.pdf

[106] Adrian Berry, *The next 500 years: life in the coming millennium*. New York: WH Freeman and Co. (1996)

[107] Sarah Berry, Sitting is the new smoking. *Sydney Morning Herald*, (2013) http://www.smh.com.au/lifestyle/life/sitting-is-the-new-smoking-20130529-2nca0.html

[108] Stanley M Besen, Joseph Farrell, Choosing how to compete: strategies and tactics in standardization. *Journal of Economic Perspectives*, 8:2 117-131, (1994)

[109] James Bessen, *Learning by Doing: The Real Connection between Innovation, Wages, and Wealth*: Yale University Press. (2015)

[110] James Bessen, Michael James Meurer, *Patent failure: How judges, bureaucrats, and lawyers put innovators at risk*: Princeton University Press. (2008)

[111] James Bessen, Alessandro Nuvolari, *Diffusing new technology without dissipating rents: some historical case studies of knowledge sharing*, http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2433567, 2014

[112] Federico Biagi, *ICT and Productivity: A Review of the Literature*. Luxembourg: Institute for Prospective Technological Studies, European Commission, (2013)

[113] Derek Bickerton, *Adam's tongue: how humans made language, how language made humans*. New York: Hill and Wang. (2009)

[114] Tom Biegler, Dong-Ke Zhang, *The hidden costs of electricity: externalities of power generation in Australia*: Australian Academy of Technological Science and Engineering. (2009)

[115] Wiebe E Bijker, Thomas P Hughes, Trevor Pinch, editors *The social construction of technological systems: new directions in the sociology and history of technology*. Anniversary edition ed. Cambridge MA: MIT Press. (2012)

[116] Wiebe E Bijker, John Law, *Shaping technology/building society: studies in sociotechnical change*. Cambridge MA: MIT Press. (1992)

[117] Karin Bijsterveld, Acoustic cocooning: How the car became a place to unwind. *Senses and Society*, 5:2 189-211, (2010)

[118] Michaël Bikard Is Knowledge Trapped Inside the Ivory Tower? Technology Spawning and the Genesis of New Science-Based Inventions MIT Sloan School of Management, (2012)

[119] Nick Bilton, Bits pics: Kodak's 1975 model digital camera, http://bits.blogs.nytimes.com/2010/08/26/bits-pics-kodaks-1975-model-digital-camera/?_r=1

[120] Binmore, Klemperer, The Biggest Auction Ever: the Sale of the British 3G Telecom Licences. *The Economic Journal*, 112:478 C74-C96, (2002)

[121] BITRE, *Road Deaths Australia 2013 Statistical Summary BITRE*. Canberra, ACT: Bureau of Infrastructure, Transport and Regional Economics, (2013)

[122] Richard B. Du Boff, The Introduction of Electric Power in American Manufacturing. *The Economic History Review*, 20:3 509-518, (1967)

[123] Ian Bogost, The secret history of the robot car, 14 October 2014, http://www.theatlantic.com/magazine/archive/2014/11/the-secret-history-of-the-robot-car/380791/

[124] Michele Boldrin, David K. Levine, The Case Against Patents. *Journal of Economic Perspectives*, 27:1 3-22, (2013)

[125] Henry A.H. Boot, John T. Randall, Historical Notes on the Cavity Magnetron. *IEEE Transactions on Electron Devices*, 23:7 724-729, (1976)

[126] Kevin L Borg, *Auto Mechanics: Technology and Expertise in Twentieth-Century America*; Philip B. Scranton, editor. Baltimore: The John Hopkins University Press. (2007)

[127] Bos Frits, Teulings Coen, *CBP and Dutch fiscal policy in view of the financial crisis and aging*. The Hague, The Netherlands: CBP Netherlands Bureau for Economic Policy Analysis, (2010)

[128] David Boud, Grahame Feletti, *The challenge of problem-based learning*. London: Kogan Page Limited. (1998)

[129] Marcel Boumans, How to design Galilean fall experiments in economics. *Philosophy of Science*, 70:2 308-329, (2003)

[130] Geoffrey C Bowker, Karen Baker, Florence Millerand, David Ribes, Toward information infrastructure studies: Ways of knowing in a networked environment. *International Handbook of Internet Research*: Springer. pp. 97-117 (2010)

[131] Geoffrey C Bowker, Susan Leigh Star, *Sorting things out: classification and its consequences*. USA: MIT Press. (2000)

[132] Ernest L Boyer, *Scholarship reconsidered: priorities of the professoriate*. New York: Carnegie Foundation for the Advancement of Teaching, (1990)

[133] Nenad Bozinovic, Yang Yue, Yongxiong Ren, Moshe Tur, Poul Kristensen, et al., Terabit-scale orbital angular momentum mode division multiplexing in fibers. *Science*, 3401545-1548, (2013)

[134] John Braithwaite, Peter Drahos, *Global business regulation*: Cambridge University Press. (2000)

[135] Allison Bramwell, David A Wolfe, Universities and regional economic development: the entrepreneurial University of Waterloo. *Research Policy*, 37:8 1175-1187, (2008)

[136] Steward Brand, *How Buildings Learn: What happens after they're built*: Penguin books. (1995)

[137] Jonathan Breckon, *Better public services through experimental government*. Alliance for Useful Research, (2015)

[138] Timothy Bresnahan, General Purpose technologies. *Handbooks in Economics*: Elsevier. pp. 761-791 (2010)

[139] Timothy F Bresnahan, Manuel Trajtenberg, General purpose technologies 'Engines of growth'? *Journal of econometrics*, 65:1 83-108, (1995)

[140] William J Broad, *The Oracle: the lost secrets and hidden message of ancient Delphi*. New York: Penguin Press. (2006)

[141] R. P. Broadhurst, M. Alazab Grabosky, S. Chon, Organizations and Cybercrime: An Analysis of the Nature of Groups engaged in Cyber Crime. *International Journal of Cyber Criminology*, 8:1 1-20, (2014)

[142] Nik Brown, Mike Michael, A sociology of expectations: retrospecting prospects and prospecting retrospects. *Technology Analysis and Strategic Management*, 15:1 3-18, (2003) http://research.gold.ac.uk/2379/

[143] Tim Brown, *Change by design: how design thinking transforms organizations and inspires innovation*: Harper-Collins. (2009)

[144] Gordana Bruce, Christine Critchley, *The Swinbourne National Technology and Society Monitor 2013*. Swinbourne University of Technology, (2013)

[145] Erik Brynjolfsson, Andrew McAfee, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*. New York: W.W. Norton and Company. (2014)

[146] Andreja Bubic, D Yves von Cramon, Ricarda I Schubotz, Prediction, cognition and the brain. *Frontiers in Human Neuroscience*, 4, (2010)

[147] Louis L Bucciarelli, *Designing engineers*. Cambridge MA: MIT Press. (1996)

[148] Randy L. Buckner, Daniel C. Carroll, Self-projection and the brain. *Trends in Cognitive Sciences*, 11:2, (2006)

[149] Harun Bulut, GianCarlo Moschini, *U.S. universities' net returns from patenting and licensing: a quantile regression analysis*. Center for Agricultural and Rural Development, Iowa State University, (2006) http://www.card.iastate.edu/publications/synopsis.aspx?id=1024

[150] Bureau of Meteorology, *Detailed reports on notable Quennsland Floods*. (2014) http://www.bom.gov.au/qld/flood/fld_history/

[151] John Burnham, *Accident prone: a history of technology, psychology, and misfits of the machine age*. Chicago and London: University of Chicago Press. (2010)

[152] Russell W Burns, *The Struggle for Unity: Colour television, the formative years*. London: Institution of Engineering and Technology. (2008)

[153] Robert A Burton, *On being certain: believing you are right even when you're not*. New York: St Martin's Press. (2008)

[154] John Bagnell Bury, *The idea of progress: An inquiry into its origin and growth*: Macmillan. (1920)

[155] Liam Byrnes, Colin Brown, John Foster, Liam Wagner, Australian Renewable Energy Policy: Barriers and Challenges. *Renewable Energy*, 60711-721, (2013)

[156] Werner Callebaut, Diego Rasskin-Gutman, editors *Modularity: understanding the development and evolution of natural complex systems*. Cambridge MA: MIT Press. (2005)

[157] Donald T Campbell, Reforms as experiments. *American Psychologist*, 24409-429, (1969)

[158] Donald T Campbell, Methods for the experimenting society. *American Journal of Evaluation*, 12:3 223-260, (1991)

[159] Katherine Campbell, Duane Helleloid, An exercise to explore the future impact of new technologies. *Journal of Product Innovation Management*, 19:1 69-80, (2002)

[160] Chiara Candelise, Mark Winskel, Robert JK Gross, The dynamics of solar PV costs and prices as a challenge for technology forecasting. *Renewable and Sustainable Energy Reviews*, 2696-107, (2013)

[161] Mark D Cannon, Amy C Edmondson, Failing to learn and learning to fail (intelligently): how great organizations put failure to work to innovate and improve. *Long Range Planning*, 38299-319, (2005)

[162] James Canton The extreme future: the top trends that will reshape the world in the next 20 years. New York: Penguin, (2006)

[163] W.Bernard Carlson, Artifacts and Frames of Meaning: Thomas A. Edison, His Managers, and the Cultural Construction of Motion Pictures. In: Wiebe E Bijker, John Law, editors. *Shaping technology/building society: Studies in sociotechnical change*. Cambridge: MIT press (1992)

[164] Nicholas Carr, Reverse salients and technological innovation, 2 September 2011, http://www.nicholasgcarr.com/digital_renderings/archives/reverse_salients_and.shtml

[165] Michael Carter Technological change in Australia: A review of the Myers Report. Discussion Paper Number 20: The Centre for Economic Policy Research, The Australian National University, (No date)

[166] Manuel Castells, *The information age: Economy, society and culture. Volume I, The Rise of the Network Society*: Wiley-Blackwell. (1998)

[167] Manuel Castells, *Communication power*. Oxford: Oxford University Press. (2013)

[168] Manuel Castells, *The impact of the internet on society: a global perspective*, https://http://www.bbvaopenmind.com/en/article/the-impact-of-the-internet-on-society-a-global-perspective/?fullscreen=true, 2015

[169] Jonathan Cave, C Van Oranje, Rebecca Schindler, Alaa Shehabi, Philipp-Bastian Brutscher, et al., Trends in connectivity technologies and their socio-economic impacts. *DG Information Society and Media*, (2009)

[170] Centers for Disease Control and Prevention, *Tobacco-Related Mortality*, 30 May 2015, http://www.cdc.gov/tobacco/data_statistics/fact_sheets/health_effects/tobacco_related_mortality/

[171] Paul E Ceruzzi, An unforeseen revolution: computers and expectations, 1935–1985. In: Joseph J Corn, editor. *Imagining tomorrow: history, technology, and the American future*. Cambridge MA: MIT Press. pp. 188–201 (1986)

[172] Paul E Ceruzzi, *A history of modern computing*. Cambridge MA: MIT Press. (1998)

[173] Paul E. Ceruzzi, Moore's law and technological determinism: reflections on the history of technology. *Technology and Culture*, 46:3 584-593, (2005)

[174] Bill Chamberlin, HorizonWatching: how IBM develops views of the potential futures, 17 August 2011, http://www.slideshare.net/HorizonWatching/horizonwatching-how-ibm-develops-views-of-the-potential-futures

[175] TC Chamberlin, The method of multiple working hypotheses. *Science*, 15:366 92-96, (1890)

[176] N Chaudhary, KK Nakka, N Maulik, S Chattopadhyay, Epigenetic manifestation of metabolic syndrome and dietary management. *Antioxid Redox Signal*, 17:2 254-281, (2012)

[177] Ross E Cheit, *Setting safety standards: Regulation in the public and private sectors*. Berkeley: University of California Press. (1990)

[178] Henry Chesbrough, Wim Vanhaverbeke, Joel West, editors *Open innovation: researching a new paradigm*. Oxford: Oxford University Press. (2006)

[179] Henry William Chesbrough, *Open innovation: the new imperative for creating and profiting from technology*. Boston: Harvard Business Press. (2003)

[180] Chief Scientist, *Strategic Science and Research Priorities*, April 2015, http://www.chiefscientist.gov.au/wp-content/uploads/STRATEGIC-SCIENCE-AND-RESEARCH-PRIORITIES_181214web.pdf

[181] Karim Chime, Open science in the cloud: towards a universal platform for scientific and statistical computing. In: B Furht, A Escalante, editors. *Handbook of cloud computing*. USA: Springer. pp. 453–474 (2010)

[182] Charles Choi, *Quantum computers check each other's work*, http://news.sciencemag.org/physics/2013/09/quantum-computers-check-each-other%E2%80%99s-work, 2013

[183] Clayton Christensen, *The innovator's dilemma: when new technologies cause great firms to fail*: Harvard Business Review Press. (2013)

[184] Clayton M Christensen, *The innovator's dilemma: when new technologies cause great firms to fail*. Boston MA: Harvard Business School Press. (1997)

[185] Brian Christian The A/B test: inside the technology that's changing the rules of business. Wired Magazine, (2012)

[186] Brian Christian, *Test everything: notes on the A/B revolution*, http://www.wired.com/2012/05/test-everything/, 2012

[187] Brittany M. Christian, Lynden K. Miles, Fiona Hoi Kei Fung, Sarah Best, C. Neil Macrae, The shape of things to come: exploring goal-directed prospection. *Consciousness and Cognition*, 22471–478, (2013)

[188] Arthur C Clarke, *Profiles of the future* London: Victor Gollancz. (1962)

[189] Arthur C Clarke, Hazards of prophecy. In: Alvin Toffler, editor. *The Futurists*. first published 1962 ed. New York: Random House. pp. 133-150 (1972)

[190] Jeff Clune, Jean-Baptiste Mouret, Hod Lipson, The evolutionary origins of modularity. *Proceedings of The Royal Society B*, 280, (2013)

[191] Joseph F. Coates, A 21st Century Agenda for Technology Assessment. *Technological Forecasting and Social Change*, 67303-308, (2001)

[192] Vary T Coates, Bernard S Finn, *A retrospective technology assessment: submarine telegraphy - the transatlantic cable of 1866*. San Francisco: San Francisco Press. (1979)

[193] Thomas C. Cochran, The Social Impact of the Railroad. In: Bruce Mazlish, editor. *The railroad and the space program: An exploration in historical analogy*: MIT Press. pp. 163-181 (1965)

[194] Jeffrey A. Cohen, *Intangible Assets: Valuation and Economic Benefit*. New Jersey: John Wiley & Sons, Inc. (2005)

[195] John Colapinto, *Material question*, http://www.newyorker.com/magazine/2014/12/22/material-question, 2014

[196] David Collingridge, *The social control of technology*: Pinter London. (1980)

[197] Barbara Combs, Paul Slovic, Newspaper coverage of causes of death. *Journalism Quarterly*, 56:4 837, (1979)

[198] Diego Comin, Bart Hobijn, Cross-country technology adoption: making the theories face the facts. *Journal of Monetary Economics*, 51:1 39-83, (2004)

[199] Diego Comin, Bart Hobijn, Emilie Rovito Five facts you need to know about technology diffusion. National Bureau of Economic Research, (2006)

[200] Committee of Inquiry into Technological Change in Australia, *Technological change in Australia, Vols 1-4*. Canberra, (1980)

[201] Committee on Forecasting Future Disruptive Technologies: National Research Council, *Persistent forecasting of disruptive technologies*. Washington DC: Committee on Forecasting Future Disruptive Technologies: National Research Council, (2010)

[202] Commonwealth Attorney-General, *National Plan to Combat Cybercrime*. Canberra, (2013) http://www.ag.gov.au/CrimeAndCorruption/Cybercrime/Documents/National Plan to Combat Cybercrime.pdf

[203] Commonwealth of Australia, *Handbook of Cost-Benefit Analysis, January 2006*. (2006)

[204] Commonwealth of Australia, *Financial System Inquiry: Final Report*. Commonwealth of Australia, (2014) http://fsi.gov.au/publications/final-report/

[205] Kieran Conboy, Brian Fitzgerald. Toward a conceptual framework of agile methods: a study of agility in different disciplines. 2004 ACM workshop on Interdisciplinary software engineering research. ACM. pp. 37-44,

[206] Edward W Constant, Why evolution is a theory about stability: constraint, causation, and ecology in technological change. *Research Policy*, 31:8 1241-1256, (2002)

[207] Melvin E Conway, How do committees invent? *Datamation*, 14:5 28-31, (1968) http://www.melconway.com/research/committees.html

[208] Richard Cooke, *Much obliged*, http://www.themonthly.com.au/issue/2014/november/1414760400/richard-cooke/much-obliged, 2014

[209] C Cormick, Public Attitudes towards GM crops and food. *Agricultural Science*, 21:2 24-30, (2007)

[210] Joseph J Corn, editor *Imagining tomorrow: history, technology, and the American future*. Cambridge MA: MIT Press. (c1986)

[211] Joseph J Corn, Brian Horrigan, *Yesterday's tomorrows: past visions of the American future*. Baltimore: Johns Hopkins University Press. (1996)

[212] National Research Council, *Big Data in Materials Research and Development*: The National Academies Press. (2014)

[213] National Research Council, *Industrialization of Biology: A roadmap to accelerate the advanced manufacturing of chemicals*: The National Academies Press. (2015)

[214] Rachel Courtland, The status of Moore's Law: it's complicated. *IEEE Spectrum*, (2013) http://spectrum.ieee.org/semiconductors/devices/the-status-of-moores-law-its-complicated/

[215] R. Cowan, and Gunby, P Sprayed to Death: Pest Control Strategies and Technological Lock-In. *Economic Journal*, 106:436 521-542, (1996)

[216] Robin Cowan, Paul A David, Dominique Foray, The explicit economics of knowledge codification and tacitness. *Industrial and Corporate Change*, 9:2 211-253, (2000)

[217] Robin Cowan, Staffan Hulten, Escaping lock-in: the case of the electric vehicle. *Technological Forecasting and Social Change*, 53:1 61-79, (1996)

[218] Ruth Schwartz Cowan, From Virginia Dare to Virginia Slims: women and technology in American life. *Technology and Culture*, 51-63, (1979)

[219] Ruth Schwartz Cowan, *More work for mother: the ironies of household technology from the open hearth to the microwave*. New York: Basic Books. (1983)

[220] Ruth Schwartz Cowan, How the refrigerator got its hum. In: Donald MacKenzie, Judy Wajcman, editors. *The social shaping of technology*: Open University Press (1999)

[221] Nicholas Crafts, The contribution of new technology to economic growth: lessons from economic history. *Journal of Iberian and Latin American Economic History*, 28:3 409-440, (2010)

[222] Cramton, *Spectrum Auctions"*. . 605–649 p. (2001)

[223] Gustavo Crespi, Alessandro Maffioli, Pierre Mohnen, Gonzalo Vazquez, *Evaluating the impact of science, technology and innovation programs: a methodological toolkit*. Inter-American Development Bank, (2011)

[224] Mariëlle EH Creusen, Jan PL Schoormans, The different roles of product appearance in consumer choice. *Journal of Product Innovation Management*, 22:1 63-81,

[225] Christine Critchley, Lyn Turney, Understanding Australians' perceptions of controversial scientific research. *Australian Journal of Emerging Technologies and Society*, 2:2 82-107, (2004)

[226] Laura Cruz-Castro, Luis Sanz-Menendez, *Bridges between Science, Society and Policy - Shaping the Impact: the Institutional Context of Technology Assessment*. (2004)

[227] Mihaly Csikszentmihalyi, *Creativity: Flow and the psychology of discovery and invention*: Harper. (1997)

[228] CSIRO A world without wires. Australia: CSIRO, (2014)

[229] Kenneth Cukier, Mayer-Schoenberger, The rise of big data: how it's changing the way we think about the world. *Foreign Affairs*:May-June 28-40, (2013)

[230] Cullens, *The AIM Incentive*, http://www.cullens.com.au/news-events/ideas-into-assets-r-blog/the-aim-incentive/

[231] Mary Ann Curran, *Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products*. New Jersey: Scrivener Publishing and John Wiley and Sons Inc. (2012)

[232] Mike Cushman, Ela Klecun, How (can) non-users engage with technology: bringing in the digtially excluded. In: E Trauth, D Howcroft, B Butler, B Fitzgerald, J DeGross, editors. *Social inclusion: societal and organizational implications for information systems*. Boston, USA: Springer. pp. 347-364 (2006)

[233] Cutting Red Tape, *Ten principles for Australian Government policy makers*, March 2015, https://cuttingredtape.gov.au/handbook/ten-principles-australian-government-policy-makers

[234] Tugrul U Daim, Guillermo Rueda, Hilary Martin, Pisek Gerdsri, Forecasting emerging technologies: use of bibliometrics and patent analysis. *Technological Forecasting and Social Change*, 73:8 981-1012, (2006)

[235] John Daley, Tristan Edis, J. Reichl, *Learning the hard way: Australia's policies to reduce emissions*. Melbourne: Grattan Institute, (2011)

[236] Norman Dalkey, Olaf Helmer, An experimental application of the Delphi method to the use of experts. *Management Science*, 9:3 458-467, (1963)

[237] Avi Dan, Kodak failed by asking the wrong marketing question, http://www.forbes.com/sites/avidan/2012/01/23/kodak-failed-by-asking-the-wrong-marketing-question/

[238] Charles Darwin, Alfred Wallace, On the Tendency of Species to form Varieties; and on the Perpetuation of Varieties and Species by Natural Means of Selection *Journal of the Proceedings of the Linnean Society of London Zoology*, 345-62, (1858) http://darwin-online.org.uk/content/frameset?itemID=F350&viewtype=text&pageseq=1

[239] Paul David, Heroes, herds and hysteresis in technological history: Thomas Edison and 'The Battle of the Systems' reconsidered. *Industrial and Corporate Change*, 1:1, (1992)

[240] Paul A David, Clio and the economics of QWERTY. *American Economic Review*, 75:2, (1985)

[241] Paul A David, The dynamo and the computer: an historical perspective on the modern productivity paradox. *American Economic Review*, 80:2 355-361, (1990)

[242] Paul A David, Why are Institutions the 'carriers of history'?: path dependence and the evolution of conventions, organizations and institutions. *Structural Change and Economic Dynamics*, 5:2 205-219, (1994)

[243] Paul A David Path dependence, its critics and the quest for 'historical economics'. (2000)

[244] Paul A David, Path dependence in economic processes: implications for policy analysis in dynamical system contexts. In: Kurt Dopfer, editor. *The evolutionary foundations of economics*. Cambridge: Cambridge University Press (2005)

[245] Paul A David, Path dependence: a foundational concept for historical social science. *Cliometrica, Journal of Historical Economics and Econometric History*, 1:2 91-114, (2007)

[246] Paul A David, Julie Ann Bunn, The economics of gateway technologies and network evolution: Lessons from electricity supply history. *Information economics and policy*, 3:2 165-202, (1988)

[247] Paul A David, Shane Greenstein, The economics of compatibility standards: an introduction to recent research. *Economics of Innovation and New Technology*, 13-41, (1990)

[248] Paul A. David Digital Technology and the Productivity Paradox: After ten years what has been learned? Understanding the Digital Economy: Data, Tools and Research. U.S. Department of Commerce, Washington D.C., (1999)

[249] Paul A. David, Path dependence - a foundational concept for historical social science. *Cliometrica, Journal of Historical Economics and Econometric History*, 1:2 91-114, (2007)

[250] Huw T.O. Davies, Sandra M. Nutley, Peter C. Smith, editors *What Works? Evidence-based policy and practice in public services*. Bristol, UK: The Policy Press. (2000)

[251] Douglas D Davis, Charles A Holt, Experimental economics: methods, problems, and promise. *Estudios Económicos*, 8:2 179-212, (1993)

[252] Andries De Grip, Jasper Van Loo, The economics of skills obsolescence: a review. *Research in labor economics*, 211-26, (2002)

[253] Gerard Debreu, *Theory of value: An axiomatic analysis of economic equilibrium*: Yale University Press. (1959)

[254] Emmanuel Dechanaux, Brent Goldfarb, Scott Shane, Marie Thursby, Appropriability and commercialization: evidence from MIT inventions. *Management Science*, 54:5 893-906, (2008)

[255] Edward L Deci, Effects of externally mediated rewards on intrinsic motivation. *Journal of Personality and Social Psychology*, 18:1 105-115, (1971)

[256] Ozgur Dedehayir, Bibliometric study of the reverse salient concept. *Journal of Industrial Engineering and Management*, 2:3, (2009)

[257] Defense Science Board, *Task Force Report: The Role of Autonomy in DoD Systems*. US Department of Defense, (2012)

[258] Alexander Degelsegger, Helge Torgersen Instructions for being unhappy with PTA—The impact on PTA of Austrian technology policy experts´ conceptualisation of the public. Vienna: Institute of Technology Assessment (ITA), (2010)

[259] Trudy Dehue, Establishing the experimenting society: the historical origin of social experimentation according to the randomized controlled design. *American Journal of Psychology*, 114:2 283-302, (2001)

[260] Michael Deker, Miltos Ladikas, *Bridges between Science, Society and Policy Technology Assessment - Methods and Impacts*; Carl Friedrich Gethmann, editor. Berlin: Springer. (2004)

[261] Luca Del Frate, Failure: analysis of an engineering concept. Delft: Technische Universiteit Delft, (2014)

[262] Juan E del Llano-Señarís, Carlos Campillo-Artero, *Health technology assessment and health policy today: a multifaceted view of their unstable crossroads*. Cham: Springer. (2015)

[263] Deloitte, *Why change now? Preparing for the workforce of the future*. Deloitte Development LLC, (2009)

[264] Deloitte, *Digital disruption: short fuse, big bang?* Sydney: Deloitte, (2012)

[265] Deloitte, *How do you value an icon? The Sydney Opera House: economic, cultural and digital value*. (2013)

[266] Deloitte, *Technology, media and telecommunications predictions 2014*. London: Deloitte Touche Tomatsu, (2014)

[267] Laura DeNardis, editor *Opening standards: the global politics of interoperability*. Cambridge MA: MIT Press. (2011)

[268] Laura DeNardis, The social stakes of interoperability. *Science*, 3371454-1455, (2012)

[269] Department of Education, Department of Industry, *Boosting the commercial returns from research*. Australian Government, (2014) http://www.industry.gov.au/industry/Documents/Boosting-Commercial-Returns-from-Research.pdf

[270] Department of Energy and Water Supply Powering Queensland's future: The 30-year electricity strategy. Discussion paper.: Queensland Government, (2013) http://www.dews.qld.gov.au/__data/assets/pdf_file/0004/96484/30yr-strategy-discussion-paper.pdf

[271] Department of Environment and Primary Industries, *Agriculture: What is organic farming*, 4 February 2014, http://www.dpi.vic.gov.au/agriculture/farming-management/organic-farming/introduction-to-organics/what-is-organic-farming

[272] Water Department of Environment, Heritage and the Arts,, *Waste Technology and Innovation Study*. Sydney: Department of Environment, Water, Heritage and the Arts, (2009)

[273] Department of Finance and Administration, *Introduction to cost-benefit analysis and alternative evaluation methodologies*. (2006) http://www.finance.gov.au/finframework/docs/Intro_to_CB_analysis.pdf

[274] Department of Human Services, *Australian Childhood Immunisation Register (ACIR) statistics*, 13 February 2015, http://www.humanservices.gov.au/corporate/statistical-information-and-data/australian-childhood-immunisation-register-statistics/?utm_id=9

[275] Department of Infrastructure and Regional Development, *Standardisation of Australia's interstate track gauge*, http://www.infrastructure.gov.au/rail/trains/history.aspx - anc_track

[276] Department of the Parliamentary Library, *A spirit of progress? Assessing Australian rail transport policy*. Canberra: Commonwealth of Australia, (1995)

[277] Department of the Prime Minister and Cabinet, *National Security Science and Innovation Strategy*. Canberra: Australian Government, (2009)

[278] Warren D Jnr Devine, From shafts to wires: historical perspectives on electrification. *Journal of Economic History*, 43:2 347-372, (1983)

[279] Patrick Devine-Wright, Reconsidering public attitudes and public acceptance of renewable energy technologies: a critical review. *Manchester: School of Environment and Development, University of Manchester Available at:* http://wwwsedmanchesteracuk/research/beyond_nimbyism, (2007)

[280] Nicholas Dew, SD Sarasvathy, S Venkataraman, The economic implications of exaptation. *Journal of Evolutionary Economics*, 1469–84, (2004)

[281] BS Dhillon, *Applied reliability and quality: fundamentals, methods and procedures*. London: Springer-Verlag. (2007)

[282] Mark Diesendorf The base-load fallacy. ANZSEE Solar 2007 Conference. Alice Springs, (2007)

[283] DIISR, *Creative industries, a strategy for 21st century Australia*. Department of Innovation, Industry, Science and Research, (2011)

[284] DIISRTE, *The National Survey of Research Commercialisation 2010-2011*. Canberra: Department of Industry, Innovation, Science, Research and Tertiary Education, (2011)

[285] DIISRTE, *2012 National Research Investment Plan*. Canberra: Department of Industry, Innovation, Science, Research and Tertiary Education, (2012)

[286] DIISRTE, *Enabling technology futures: a survey of the Australian technology landscape*. Canberra: Department of Industry, Innovation, Science, Research and Tertiary Education, (2012)

[287] Francesco Dinuzzo, Mathieu Sinn, Yannig Goude, Matthias Seeger, *ICML2015 Workshop on Demand Forecasting*, 14 July 2015, https://sites.google.com/site/icmldemand/

[288] Kate Distin, *Cultural evolution*: Cambridge University Press. (2010)

[289] Leo Dobes, A century of Australian cost-benefit analysis. *Office of Best Practice Regulation, Working Paper*, (2008)

[290] Docker, *What is Docker*, April 2015, https://http://www.docker.com/whatisdocker/

[291] DOCSIS, *Data-over-cable service interface specifications v 3.1: MAC and Upper Layer Protocols Interface Specification*. Cable Television Laboratories, (2013) http://www.cablelabs.com/wp-content/uploads/specdocs/CM-SP-MULPIv3.1-I01-131029.pdf

[292] Cory Doctorow, Will.I.Am, Douglas Rushkoff, Brian David Johnson, editors *The Tomorrow Project anthology: conversations about the future*: Richard Bowles. (2011)

[293] Jago Dodson, Neil Sipe, Oil vulnerability in the Australian city: Assessing socioeconomic risks from higher urban fuel prices. *Urban Studies*, 44:1 37-62, (2007)

[294] Gary Donnison, Peter Bryant, Comment (on the Myers Committee Report). *Australian Left Review*, 751-5, (1981)

[295] Nicholas M Donofrio, Kate S Whitefoot, *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work*. National Academy of Engineering, (2015)

[296] Kurt Dopfer, *The evolutionary foundations of economics*: Cambridge University Press. (2005)

[297] Giovanni Dosi, Technological paradigms and technological trajectories. *Research Policy*, 11147-162, (1982)

[298] Giovanni Dosi, Sources, procedures, and microeconomic effects of innovation. *Journal of Economic Literature*, 261120-1171, (1988)

[299] Giovanni Dosi, Opportunities, incentives and the collective patterns of technological change. *Economic Journal*, 1071530-1547, (1997)

[300] Giovanni Dosi, Patrick Llerena, Mauro Sylos Labini, The relationships between science, technologies and their industrial exploitation: an illustration through the myths and realities of the so-called 'European Paradox'. *Research Policy*, 35:10 1450–1464, (2006)

[301] Giovanni Dosi, Luigi Marengo, Giogio Fagiolo, *Learning in evolutionary environments*. LEM Working Paper Series, (2001)

[302] Giovanni Dosi, Richard R Nelson, Technical change and industrial dynamics as evolutionary processes. *Handbook of the Economics of Innovation*, 151-127, (2009)

[303] Giovanni Dosi, Richard R Nelson, The evolution of technologies: an assessment of the state-of-the-art. *Eurasian Business Review*, 3:1 3-46, (2013)

[304] Dale Dougherty, The maker mindset. In: Margaret Hone, David E Kanter, editors. *Design, make, play: growing the next generation of STEM innovators*. New York: Routledge (2013)

[305] Kirsty Douglas Digital computing, modelling and simulation. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2015) http://acola.org.au/index.php/new-technologies-contributing-reports

[306] Kirsty Douglas Technologies for Data. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2015) http://acola.org.au/index.php/new-technologies-contributing-reports

[307] David M Dow, *Australia advances*: Funk & Wagnalls Company. (1938)

[308] Anne-Maree Dowd, Naomi Boughen, Peta Ashworth, Simone Carr-Cornish, Geothermal technology in Australia: investigating social acceptance. *Energy Policy*, 39:10 6301-6307, (2011)

[309] Jason Dowling, *Expert report on insulation could have spared lives*, http://www.smh.com.au/federal-politics/political-news/expert-report-on-insulation-could-have-spared-lives-20120220-1tjow.html, 2012

[310] David M. Driesen, *Is Cost-Benefit Analysis Neutral?* , (2006) http://surface.syr.edu/lawpub/17

[311] Peter F. Drucker, *Management Challenges of the 21st Century*. USA: HarperCollins. (1999)

[312] William N Dunn, editor *The experimenting society: essays in honor of Donald T Campbell* Transaction Publishers. (1997)

[313] William N Dunn, Campbell's experimenting society: prospect and retrospect. In: William N Dunn, editor. *The experimenting society: essays in honor of Donald T Campbell*. New Brunswick: Transaction Publishers. pp. 1-34 (1998)

[314] John Dupré, *The disorder of things: Metaphysical foundations of the disunity of science*. USA: Harvard University Press. (1995)

[315] William H. Dutton, Ginette Law, Gillian Bolsover, Soumitra Dutta, *The Internet Trust Bubble: Global Values, Beliefs and Practices*. World Economic Forum, (2013)

[316] MA Dutz, Y Kuznetsov, E Lasagabaster, D Pilat, editors *Making innovation policy work: learning from experimentation*. Washington DC: OECD. (2014)

[317] Carol S. Dweck, Ellen L. Leggett, A social-cognitive approach to motivation and personality. *Psychological Review*, 95:2 256-273, (1988)

[318] Joe Dysart, How lawyers are mining the information mother lode for pricing, practice tips and predictions. *ABA Journal*, (2013) http://www.abajournal.com/magazine/article/the_dawn_of_big_data/

[319] Laurel Evelyn Dyson. Cultural issues in the adoption of information and communication technologies by Indigenous Australians. Proceedings Cultural Attitudes towards Communication and Technology. Murdoch University Perth. pp. 58-71,

[320] The Economist, Digital disruption on the farm. *The Economist*, (2014)

[321] David Edgerton, *The shock of the old: technology and global history since 1900*. London: Profile Books. (2008)

[322] Thomas A. Edison, The phonograph and its future. *North American Review*, 126527-536, (1878) https://archive.org/details/jstor-25110210

[323] Thomas A. Edison, The perfected phonograph. *North American Review*, 146641-650, (1888) https://archive.org/stream/jstor-25101531/25101531#page/n7/mode/2up

[324] Paul N Edwards, 'A vast machine': standards as social technology. *Science*, 304:5672 827-828, (2004)

[325] Paul N Edwards, Steven J Jackson, Geoffrey C Bowker, Cory Knobel, *Understanding infrastructure: dynamics, tensions, and design*. University of Michigan, (2007)

[326] Elizabeth Eisenstein, *The printing press as an agent of change*. Cambridge: Cambridge University Press. (1980)

[327] Almani Elnasri, Kevin J Fox, *The contribution of research and innovation to productivity and economic growth*. (2014)

[328] Jon Elster, *Explaining technical change: A case study in the philosophy of science*: Cambridge University Press. (1983)

[329] Jon Elster, *Explaining social behavior: More nuts and bolts for the social sciences*: Cambridge University Press. (2007)

[330] Boelie Elzen, Frank W Geels, Ken Green, editors *System innovation and the transition to sustainability*. Cheltenham UK: Edward Elgar. (2004)

[331] Jan van den Ende, Wilfred Dolfsma, Technology-push, demand-pull and the shaping of technological paradigms – Patterns in the development of computing technology. *Journal of Evolutionary Economics* 1583–99, (2005)

[332] Gerald L Epstein, Restart the Congressional Office of Technology Assessment. *Science Progress*, 31, (2009)

[333] EPTA European Parlamentary Technology Assessment, EPTA European Parlamentary Technology Assessment. (2014) http://eptanetwork.org/index.php

[334] ERAA, *Enabling a market-driven smart meter rollout: ERAA smart meter Working Paper 2*. Sydney: Energy Retailers Association of Australia,

[335] Ernst & Young, *University of the future: a thousand year old industry on the cusp of profound change*. Australia, (2012)

[336] Heidi Ertl, Michael Bordt, Louise Earl, Anik Lacroix, Charlene Lonmo, et al., Towards understanding impacts of science, technology and innovation activities. *Science, technology and innovation indicators in a changing world: responding to policy needs*: OECD. pp. 101-122 (2007)

[337] Abdul Azeez Erumban, Simon B de Jong, Cross-country differences in ICT adoption: a consequence of culture? *Journal of World Business*, 41:4 302-314, (2006)

[338] EuropaBio, *Pocket guide to GM crops and policies*. EuropaBio, (2012)

[339] European Commission, *ExternE Externalities of Energy: Methodology 2005 Update*. IER Universitat Stuttgart, (2005)

[340] European Commission Proposal for a Regulation of the European Parliament and of the Council on the protection of individuals with regard to the processing of personal data and on the free movement of such data (General Data Protection Regulation). Brussels, (2012)

[341] European Parliament, *European Parlaiment - Science and Technology Options Assessment (STOA)*, http://www.europarl.europa.eu/stoa/

[342] European Science Foundation, *European evolutionary biologists rally behind Richard Dawkins' extended phenotype*, http://www.sciencedaily.com/releases/2009/01/090119081333.htm, 2009

[343] Robin J Evans Future Technology Overview. Working Paper of SAF05 Project. Melbourne: Australian Council of Learned Academies, (2014) http://acola.org.au/index.php/new-technologies-contributing-reports

[344] Jon Excell, *September 1859 - Brunel's obituary*, http://www.theengineer.co.uk/in-depth/classic-archive/september-1859-brunels-obituary/1013924.article, 2012

[345] Peter Fairley, Germany's grid: renewables-rich and rock-solid, http://spectrum.ieee.org/energywise/energy/the-smarter-grid/germanys-superstable-solarsoaked-grid

[346] Dena Fam, Abby Lopes, Juliet Willetts, Cynthia Mitchell, The challenge of system change: an historical analysis of Sydney's sewer systems. *Design Philosophy Papers*, 2, (2009)

[347] Joseph Farrell, Garth Saloner, Standardization, compatibility, and innovation. *RAND Journal of Economics*, 16:1 70-83, (1985)

[348] Joseph Farrell, Philip J Weiser, *Modularity, vertical integration, and open access policies: towards a convergence of antitrust and regulation in the internt age*. Berkeley CA: University of California at Berkeley, (2003)

[349] Wendy Faulkner The technology question in feminism: A view from feminist technology studies. Women's Studies International Forum, (2000)

[350] Federal Facilities Council, *Learning from our buildings*. NAP, (2001)

[351] Gary M Feinman, Linda Manzanilla, editors *Cultural evolution: Contemporary viewpoints*: Springer. (2000)

[352] Ulrike Felt, Keeping Technologies Out: Sociotechnical imaginaries and the formation of a national technopolitical identity. *Manuscript for the editied volume S Jasanoff & S Kim, Dreamscapes of modernity: sociotechnical imaginaries and the fabrication of power Preprint available at* http://sciencestudies *univie ac at/publikationen*, (2013)

[353] Ulrike Felt, Maximilian Fochler, What science stories do: rethinking the multiple consequences of intensified science communication. In: Patrick Baranger, Bernard Schiele, editors. *Science communication today: international perspectives, issues and strategies*. Paris: CNRS Editions. pp. 75-89 (2013)

[354] Nicholas Felton, *Consumption spreads faster today*, 10 October 2014, http://www.nytimes.com/imagepages/2008/02/10/opinion/10op.graphic.ready.html

[355] Leon Festinger, Henry Riecken, Schachter. Stanley, *When prophecy fails: a social and psychological study of a modern group that predicted the destruction of the world*. New York: Harper-Torchbooks. (1956)

[356] Richard Feynmann, What is Science? *The Physics Teacher*, 7:6 313-320, (1969)

[357] Kelly S Fielding, Anne H Roiko, Providing information promotes greater public support for potable recycled water. *Water Research*, (2014)

[358] Roy Thomas Fielding, Architectural styles and the design of network-based software architectures: University of California, Irvine, (2000)

[359] Filament, *Visually exploring the patent landscape*, April 2015, http://www.filament.com.au/patent/search/patent-landscape-search.aspx

[360] Sydney Finkelstein, *Why smart executives fail and what you can learn from their mistakes*. New York: Portfolio. (2003)

[361] Ayse Kaya Firat, Wei Lee Woon, Stuart Madnick, *Technological forecasting – a review*. Cambridge MA: Composite Information Systems Laboratory, Massachusetts Institute of Technology, (2008)

[362] Tony Fischer, Derek Byerlee, Greg Edmeades, *Crop yields and global food security: will yield increase continue to feed the world?* Canberra: Australian Centre for International Agricultural Research, (2014) http://aciar.gov.au/publication/mn158

[363] Eugene Fitzgerald, Andreas Wankerl, Carl Schramm, *Inside real innovation: how the right approach can move ideas from R&D to market — and get the economy moving*: World Scientific Publishing Co. (2011)

[364] James Fleck, John Howells, Technology, the technology complex and the paradox of technological determinism. *Technology Analysis & Strategic Management*, 13:4 523-531, (2001)

[365] Lee Fleming, Recombinant uncertainty in technological search. *Management Science*, 47:1 117-132, (2001)

[366] Flyvbjerg B, Bruzelius N, Rothengatter W, and Werner, *Megaprojects and risk: An anatomy of ambition*: Cambridge University Press. (2003)

[367] Bent Flyvbjerg, *Procedures for dealing with optimism bias in transport planning: guidance document*. London: British Department for Transport, (2004)

[368] Bent Flyvbjerg, From Nobel Prize to project management: getting risks right. *Project Management Journal*, 37:3 5-15, (2006) http://flyvbjerg.plan.aau.dk/Publications2006/Nobel-PMJ2006.pdf

[369] Bent Flyvbjerg, Curbing optimism bias and strategic misrepresentation in planning: reference class forecasting in practice. *European Planning Studies*, 16:1 3-21, (2008)

[370] Bent Flyvbjerg, Survival of the unfittest: why the worst infrastructure gets built – and what we can do about it. *Oxford Review of Economic Policy*, 25:3 344–367, (2009)

[371] Flyvbjerg Bent, Techn, From Nobel prize to project management: getting risks right. *arXiv preprint arXiv:13023642*, (2013)

[372] Bent Flyvbjerg, Massimo Garbuio, Dan Lovallo, Delusion and deception in large infrastructure projects: two models for explaining and preventing executive disaster. *California Management Review*, 51:2 170-193, (2009)

[373] Bent Flyvbjerg, Nils Bruzelius, Werner Rothengatter, *Megaprojects and risk: an anatomy of ambition*: Cambridge University Press. (2003)

[374] Bent Flyvbjerg, Mette Skamris Holm, Soren Buhl, Underestimating costs in public works projects: Error or lie? *Journal of the American Planning Association*, 68:3 279-295, (2002)

[375] Robert William Fogel, *Railroads and American economic growth: essays in econometric history*. Baltimore: Johns Hopkins Press. (1964)

[376] Tyler C Folsom. Social Ramifications of Autonomous Urban Land Vehicles. IEEE International Symposium on Technology and Society May 2011; Chicago,

[377] Vladislav Fomin, Thomas Keil, Kalle Lyytinen, Theorizing about standardization: integrating fragments of process theory in light of telecommunication standardization wars. *Sprouts Working Papers on Information Systems*, 3:10, (2003) http://sprouts.aisnet.org/3-10

[378] Dominque Foray, Francesco Lissoni, University Research and Public-Private Interaction. In: Bronwyn Hall, Nathan Rosenberg, editors. *Handbook of the Economics of Innovation*: North-Holland (2010)

[379] Robert H Frank, Why is cost-benefit analysis so controversial? *The Journal of Legal Studies*, 29:S2 913-930, (2000)

[380] Guillaume R Fréchette, Andrew Schotter, editors *Handbook of Experimental Economic Methodology*. Oxford: Oxford University Press. (2015)

[381] Shane Frederick, George Loewenstein, Ted O'Donoghue, Time Discounting and Time Preference: A Critical Review. *Journal of Economic Literature*, 40:2 351-401, (2002)

[382] Chris Freeman, Francisco Louçã, *As time goes by: from the industrial revolutions to the information revolution*. Oxford: Oxford University Press. (2001)

[383] Christopher Freeman, Schumpeter's Business Cycles and Techno-Economic Paradigms. In: Wolfgang Drechsler, Rainer Kattel, Erik S. Reinert, editors. *Techno-Economic Paradigms: essays in honor of Calota Perez*. London, New York: Anthem Press. pp. 8 (2011)

[384] J Freeman The tyranny of email: The 4000-year journey to your inbox. New York: Scribners, (2009)

[385] Marsha Freeman, The railroad and the space program. *EIR*, 25:34, (1998)

[386] Freiburg Arie, *The tools of regulation* Sydney: The Federatino Press. (2010)

[387] Walter Frick What Tesla knows that other patent holders don't. Harvard Business Review, (2014) https://hbr.org/2014/06/what-tesla-knows-that-other-patent-holders-dont/

[388] Walter Frick, *Welfare makes America more entrepreneurial*, http://www.theatlantic.com/politics/archive/2015/03/welfare-makes-america-more-entrepreneurial/388598/, 2015

[389] Ann F. Friedlaender, Macroeconomics and Microeconomics of Innovation: The Role of the Technological Environment. *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, (1986)

[390] Daniel Fujiwara, Ross Campbell, *Valuation Techniques for Social Cost-Benefit Analysis: Stated preference, revealed preference and subjective well-being approaches*. HM Treasury Department for Work and Pensions, (2011)

[391] Garrett G Gallagher S, *Disruptive Education: Technology-Enabled Univversities*. The United States Studies Centre, University of Sydney, (2013)

[392] Andrea Ganzaroli, Luciano Pilotti Exaptation as source of creativity and innovation. Back to the Future: European Academy of Management Rome, (2010)

[393] Megan Garber, *The broken windows of Uber*, http://www.theatlantic.com/technology/archive/2014/12/the-broken-windows-of-uber/383746/, 2014

[394] Linda D Garcia, *Opening standards the global politics of interoperability - Governments, the public interest, and standards setting*; Laura DeNardis, editor. (2011)

[395] Ross Garnaut, *The Garnaut Review 2011: Australia in the Global Response to Climate Change*. Cambridge University Press, (2011) http://www.garnautreview.org.au/update-2011/garnaut-review-2011.html

[396] Roberto A Garrido, María A Semeraro, Samuel M Temesgen, Marcelo R Simi, Metabolic syndrome and obesity among workers at Kanye Seventh-day Adventist Hospital, Botswana. *South African Medical Journal*, 99:5 331-334, (2009)

[397] Juliette Garside Wikipedia link to be hidden in Google under 'right to be forgotten' law. The Guardian, (2014) http://www.theguardian.com/technology/2014/aug/02/wikipedia-page-google-link-hidden-right-to-be-forgotten

[398] David Gartman, *Auto opium: a social history of American automobile design*. London: Routledge. (1994)

[399] Raghu Garud, David Ahlstrom, Technology assessment: a socio-cognitive perspective. *Journal of Engineering and Technology Management*, 14:1 25-48, (1997)

[400] Atul Gawande, *Why doctors fail* http://www.theguardian.com/news/2014/dec/02/-sp-why-doctors-fail-reith-lecture-atul-gawande, 2014

[401] Frank Geels, Co-evolution of technology and society: The transition in water supply and personal hygiene in the Netherlands (1850–1930)—a case study in multi-level perspective. *Technology in Society*, 27363-397, (2005)

[402] Frank W Geels, Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research policy*, 31:8 1257-1274, (2002)

[403] Frank W Geels, *Technological transitions and system innovations: a co-evolutionary and socio-technical analysis*. Cheltenham UK: Edward Elgar. (2005)

[404] Frank W Geels, Co-evolutionary and multi-level dynamics in transitions: the transformation of aviation systems and the shift from propeller to turbojet (1930–1970). *Technovation*, 26999-1016, (2006)

[405] Frank W Geels, The hygienic transition from cesspools to sewer systems (1840–1930): the dynamics of regime transformation. *Research Policy*, 351069-1082, (2006)

[406] Frank W Geels, Johan Schot, Typology of sociotechnical transition pathways. *Research Policy*, 36399-417, (2007)

[407] Tom Geoghegan, *Ten 100-year predictions that came true*, http://www.bbc.co.uk/news/magazine-16444966, 2012

[408] Luke Georghiou, Issues in the evaluation of innovation and technology policy. *Policy Evaluation in Innovation and Technology: Towards Best practices*: OECD (1997)

[409] Gerald P.O'Driscoll Jr, Mario J. Rizzo, *The Economics of Time and Ignorance*. London, New York: Routledge. (1996)

[410] JK Gershenson, G.J Prasadb, Y Zhang, Product modularity: definitions and benefits. *Journal of Engineering Design*, 14:3 295-313, (2003)

[411] Connie T.G. Gersick, Revolutionary change theories: a multilevel exploration of the punctuated equilibrium paradigm. *Academy of Management Review*, 16:1 10-36, (1991)

[412] Martina Gerst, Raluca Bunduchi, Robin Williams. Social shaping & standardization: a case study from auto industry. 38th Annual Hawaii International Conference on System Sciences Hawaii. IEEE. pp. 204a-204a,

[413] Keith Gessen, *The War of the Words*, http://www.vanityfair.com/news/business/2014/12/amazon-hachette-ebook-publishing, 2014

[414] Arpita Ghosh, Preston McAfee, Kishore Papineni, Sergei Vassilvitskii, Bidding for representative allocations for display advertising. *Internet and Network Economics*. Berlin: Springer. pp. 208-219 (2009)

[415] Pallab Ghosh, *'Vital' science spared deep cuts*, http://www.bbc.com/news/science-environment-11579949, 2010

[416] Gerd Gigerenzer, Dread risk, September 11, and fatal traffic accidents. *Psychological Science*, 15:4 285-286, (2004)

[417] Gerd Gigerenzer, Out of the frying pan into the fire: behavioral reactions to terrorist attacks. *Risk Analysis*, 26:2 347-351, (2006)

[418] Daniel T. Gilbert, Timothy D. Wilson, Prospection: experiencing the future. *Science Magazine*, 3171351-1354, (2007)

[419] Richard Gilbert, A world without intellectual property? A review of Michele Boldrin and David Levine's *Against Intellectual Monopoly*. *Journal of Economic Literature*, 49:2 421-432, (2011)

[420] S Colum Gilfillan, Social principles of invention (parts 1-8). *Journal of the Patent Office Society*, 16-17, (1934-35)

[421] S Colum Gilfillan, *The sociology of invention: an essay in the social causes of technic invention and some of its social results; especially as demonstrated in the history of the ship. A companion volume to the same author's Inventing the ship*. Chicago: Follett Publishing Company. (1935)

[422] SC Gilfillan, The prediction of technical change. *Review of Economics and Statistics*, 34:4 368-385, (1952)

[423] SC Gilfillan, An attempt to measure the rise of American inventing and the decline of patenting. *Technology and Culture*, 1:3 201-214, (1960)

[424] Judith Gill, Rhonda Sharp, Julie Mills, Suzanne Franzway, I still wanna be an engineer! Women, education and the engineering profession. *European Journal of Engineering Education*, 33:4 391-402, (2008)

[425] Thomas Gilovich, *How we know what isn't so: the fallibility of human reason in everyday life*. New York: The Free Press, Macmillan. (1991)

[426] Thomas Gilovich, Dale Griffin, Daniel Kahneman, editors *Heuristics and biases: the psychology of intuitive judgment* Cambridge: Cambridge University Press. (2002)

[427] Edward L Glaeser, William R Kerr, *Local industrial conditions and entrepreneurship: how much of the spatial distribution can we explain?* , (2008)

[428] Edward L Glaeser, William R Kerr, *What makes a city entrepreneurial?* : Harvard Kennedy School of Government, (2010)

[429] Paul Glen, *Leading Geeks: How to manage and lead the people who deliver technology*: Jossey-Bass. (2003)

[430] Benoit Godin Innovation and Creativity: A Slogan, Nothing but a Slogan. Project on the Intellectual History of Innovation, (2014)

[431] Benoit Godin, *Innovation contested: the idea of innovation over the centuries*: Routledge. (2015)

[432] Benoît Godin, The Linear model of innovation the historical construction of an analytical framework. *Science, Technology & Human Values*, 31:6 639-667, (2006)

[433] Benoît Godin, Joseph. P Lane, Pushes and Pulls: Hi(S)tory of the Demand Pull Model of Innovation. *Science, Technology & Human Values*, 38621, (2013)

[434] Rob Goffee, Gareth Jones, *Clever: leading your smartest, most creative people*. USA: Harvard Business Press. (2009)

[435] Claudia Goldin, Lawrence F. Katz, *The Race Between Education and Technology*. Cambridge, Massachusetts: The Belknap Press. (2008)

[436] Christian Gollier, *The Economics of Risk and Time*. Cambridge, Massachusetts: The MIT Press. (2001)

[437] Paul Goodwin, George Wright, The limits of forecasting methods in anticipating rare events. *Technological Forecasting and Social Change*, 77:3 355-368, (2010)

[438] Robert J Gordon, *The demise of US economic growth: restatement, rebuttal, and reflections*. Cambridge MA: National Bureau of Economic Research, (2014)

[439] Stephen Jay Gould, Niles Eldredge, Punctuated equilibria: the tempo and mode of evolution reconsidered. *Paleobiology*, 3115-151, (1977)

[440] Government Office for Science [UK], *Chief Scientific Advisers and their officials: an introduction*, https://http://www.gov.uk/government/uploads/system/uploads/attachment_data/file/405121/15-2-chief-scientific-advisers-and-officials-introduction.pdf, 2015

[441] Stuart JH Graham, Iacopetta. Maurizio, *Nanotechnology and the emergence of a general purpose technology*, http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1334376, 2009

[442] Christine Greenhalgh, Mark Rogers, *Innovation, intellectual property, and economic growth*. Princeton NJ: Princeton University Press. (2010)

[443] Trisha Greenhalgh, Deborah Swinglehurst, Rob Stones, Rethinking resistance to 'big IT': a sociological study of why and when healthcare staff do not use nationally mandated information and communication technologies. *Health Services and Delivery Research*, 2:39, (2014)

[444] Martin Gregory, Superseding the seamstress: the sewing machine, from invention to mass production in a generation. *International Journal for the History of Engineering and Technology*, 84:2 115-134, (2014)

[445] Tren Griffin, A dozen things I've learned from Vinod Khosla, 22 June 2014, http://25iq.com/2014/06/22/a-dozen-things-ive-learned-from-vinod-khosla/

[446] C Griffith, A Dormer, L Jakubowski, T Percival, S Kaplan, et al., *New models for digital government: the role of service brokers in driving innovation*. National Information and Communications Technology Australia (NICTA), (2014)

[447] Zvi Griliches, *Patents: recent trends and puzzles*. Cambridge MA: National Bureau of Economic Research. 291-330 p, (1989)

[448] Zvi Griliches, Patent statistics as economic indicators: a survey. In: Zvi Griliches, editor. *R&D and productivity: the econometric evidence*: University of Chicago Press. pp. 287-343 (1998)

[449] William Grimes Great 'Hello' Mystery Is Solved. The New York Times. New York, USA, (1992)

[450] Stine Grodal, Aleksios Gotsopoulos, Fernando Suarez, The Co-evolution of Technologies and Categories during Industry Emergence. *Academy of Management Review*, (2014)

[451] Matthias Gross, Wolfgang Krohn, Society as experiment: sociological foundations for a self-experimental society. *History of the Human Sciences*, 18:2 63-86, (2005)

[452] Arnulf Grübler, *The rise and fall of infrastructures: dynamics of evolution and technological change in transport*; Werner A. Müller, editor. Heidelberg: Physica-Verlag Heidelberg. (1990)

[453] Arnulf Grübler, Sabine Messner, Technological change and the timing of mitigation measures. *Energy Economics*, 20495-512, (1998)

[454] Arnulf Grübler, Nebojša Nakićenović, David G. Victor, Dynamics of energy technologies and global change. *Energy Policy*, 27247-280, (1999)

[455] Francesco Guala, *The methodology of experimental economics*. Cambridge: Cambridge University Press. (2005)

[456] John Hagel III, John Seely Brown, Lang Davison, The shift index: uncovering the emerging logic of deep change. *Deloitte Center for the Edge*, 1-15, (2009) http://www.edgeperspectives.com/shiftindex.pdf

[457] Andrei Hagiu, David B Yoffie, The new patent intermediaries: platforms, defensive aggregators, and super-aggregators. *Journal of Economic Perspectives*, 27:1 45-66, (2013)

[458] Fiona Haines, *The paradox of regulation*: Edward Elgar. (2011)

[459] Bronwyn H Hall, Adam Jaffe, Manuel Trajtenberg, Market value and patent citations. *RAND Journal of Economics*, 36:1 16-38, (2005)

[460] Bronwyn H Hall, Jacques Mairesse, Pierre Mohnen, *Measuring the returns to R&D*; Kenneth JA Arrow, Michael D Intriligator, editors. Amsterdam: Elsevier. (2010)

[461] Bronwyn H Hall, Trajtenberg Manuel, *Uncovering GPTs with patent data*. (2004)

[462] Bronwyn H. Hall, Does Patent Protection Help or Hinder Technology Transfer? *Intellectual Property for Economic Development*, 11-32, (2014)

[463] Nina Hall, Peta Ashworth, Hylton Shaw Exploring community acceptance of rural wind farms in Australia: a snapshot. CSIRO Science into Society Group, (2012)

[464] Erica Rosenfeld Halverson, Kimberly M Sheridan, The maker movement in education. *Harvard Educational Review*, 84:4 495-565, (2014)

[465] James Hamblin, *If you keep texting, your head will fall off: countering the claim that texting is ruining spines*, http://www.theatlantic.com/health/archive/2014/11/death-by-texting-spine-problems-text-neck-madness/383132/, 2014

[466] James Hamblin, *This is the average man's body*, http://www.theatlantic.com/health/archive/2013/10/this-is-the-average-mans-body/280194/, 2013

[467] Clive Hamilton, Measuring sustainable economic welfare. In: Giles Atkinson, Simon Dietz, Eric Neumayer, editors. *Handbook of Sustainable Development*. UK: Edward Elgar Publishing (2007)

[468] Tyler Hamilton, Wind gets clean bill of health, http://www.thestar.com/business/2009/12/15/wind_gets_clean_bill_of_health.html

[469] Ian Hanger, *Report of the Royal Commission into the Home Insulation Program*. Canberra: Royal Commission into the Home Insulation Program, Commonwealth of Australia, (2014)

[470] Ole Hanseth, Gateways - just as important as standards: How the internet won the 'religious war' over standards in Scandinavia. *Knowledge, Technology & Policy*, 14:3 71-89, (2001)

[471] Ole Hanseth, Edoardo Jacucci, Miria Grisot, Margunn Aanestad, Reflexive standardization: side effects and complexity in standard making. *MIS Quarterly*, 30563-581, (2006)

[472] Ole Hanseth, Eric Monteiro, Morten Hatling, Developing information infrastructure: the tension between standardization and flexibility. *Science Technology Human Values*, 21407-426, (1996) http://sth.sagepub.com/cgi/content/abstract/21/4/407

[473] Tim Harford, *Adapt: why success always starts with failure*: Little, Brown Young. (2011)

[474] Daniel M Hausman, *The inexact and separate science of economics*. Cambridge: Cambridge University Press. (1992)

[475] David Havyatt IT left out in Australia's future vision. Financial Review, (2014) http://www.afr.com/technology/itleft-out-in-australias-future-vision-20141110-11k1qc

[476] Wayne Hawkins, Broadband, disability and the role of standards. *Telecommunications Journal of Australia*, 61:2, (2011)

[477] Laura Haynes, Owain Service, Ben Goldacre, David Torgerson, *Test, learn, adapt: developing public policy with randomised controlled trials*. London: Cabinet Office [UK] Behavioural Insights Team, (2012) http://dx.doi.org/10.2139/ssrn.2131581

[478] Daniel R Headrick, *Technology: A World History*. Oxford: Oxford University Press. (2009)

[479] Tim Healy, The unanticipated consequences of technology. In: Ahmed S Khan, editor. *Nanotechnology: ethical and social implications*. Boca Raton FL: CRC Press. pp. 155-174 (2012)

[480] Olaf Helmer, *Prospects of technological progress*. Santa Monica CA: RAND Corporation, (1967)

[481] Robert L Helmreich, On error management: lessons from aviation. *BMJ*, 320781-785, (2000)

[482] Elhanan Helpman, *General purpose technologies and economic growth*: MIT Press. (1998)

[483] Elhanan Helpman, *The mystery of economic growth*. Cambridge MA: Belknap Press of Harvard University Press. (2004)

[484] Rebecca M Henderson, Kim B Clark, Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly*, 35:1 9-30, (1990)

[485] Joachim Henkel, Carliss Y Baldwin, *Modularity for value appropriation: how to draw the boundaries of intellectual property*. Boston MA: Harvard Business School, (2010)

[486] Annabel Hepworth Federal government reject advice on big projects' cost-benefit call. The Australian. Sydney, (2014)

[487] Richards J.Jr Heuer, *Psychology of intelligence analysis*: Center for the Study of Intelligence, Central Intelligence Agency. (1999)

[488] Catherine Hill, Christianne Corbett, Andresse St Rose, *Why So Few? Women in Science, Technology, Engineering, and Mathematics*: American Association of University Women. (2010)

[489] Jess Hill, *Power corrupts: how network companies lined their pockets and drove electricity prices through the roof*, http://www.themonthly.com.au/issue/2014/july/1404136800/jess-hill/power-corrupts, 2014

[490] George W Hilton, Transport technology and the urban pattern. *Journal of Contemporary History*, 4:3 123-135, (1969)

[491] HM Government Open Data White Paper: Unleashing the potential. HM Government: Minister of State for the Cabinet Office and Paymaster General, (2012)

[492] HM Revenue & Customs, *Corporation Tax: the Patent Box*, April 2015, https://http://www.gov.uk/corporation-tax-the-patent-box

[493] HM Treasury, *The green book: appraisal and evaluation in central government*. London: HM Treasury, (2013)

[494] HM Treasury and Infrastructure UK Early financial cost estimates of infrastructure programmes and projects and the treatment of uncertainty and risk. Gov.uk, (2013) https://http://www.gov.uk/government/publications/green-book-supplementary-guidance-valuing-infrastructure-spend

[495] Shirley S Ho, Dietram A Scheufele, Elizabeth A Corley, Making sense of policy choices: understanding the roles of value predispositions, mass media, and cognitive processing in public attitudes toward nanotechnology. *Journal of Nanoparticle Research*, 12:8 2703-2715, (2010)

[496] Volker H. Hoffmann, Thomas Trautmann, Jens Hamprecht, Regulatory Uncertainty: A Reason to Postpone Investments? Not Necessarily. *Journal of Management Studies*, 46:7 1227-1253, (2009)

[497] Geert Hoftede, Gert Jan Hofstede, Michael Minkov, *Cultures and organizations: software of the mind: intercultural cooperation and its importance for survival*: McGraw-Hill. (2010)

[498] Margaret Honey, David E Kanter, editors *Design, make, play: growing the next generation of STEM innovators*. New York: Routledge. (2013)

[499] Christopher Hood, *The blame game: spin, bureaucracy, and self-preservation in government*. Princeton: Princeton University Press. (2011)

[500] Wes Hosking Smart meter shock forces family out. Herald Sun, (2011) http://www.heraldsun.com.au/ipad/smart-meter-shock-forces-family-out/story-fn6bfm6w-1226181905576

[501] Shaikat Hossain, Cochlear implants and the deaf culture: a transhumanist perspective, 11 June 2012, http://humanityplus.org/

[502] William G Howard, Bruce R Guile, editors *Profiting From Innovation: The report of the three-year study from the National Academy of Engineering*. New York: The Free Press. (2010)

[503] Michael JA Howe, *Genius explained*: Cambridge University Press. (1999)

[504] John Howells, *The management of innovation and technology: the shaping of technology and institutions of the market economy*. London, California, New Dehli: Sage Publications. (2005)

[505] Michael Howlett, Why are policy innovations rare and so often negative? Blame avoidance and problem denial in climate change policy-making. *Global Environmental Change*, 29395–403, (2014)

[506] Katherine Hoye, University intellectual property policies and university-industry technology transfer in Canada: University of Waterloo, (2006)

[507] John Hughes, Why functional programming matters. In: D Turner, editor. *Research topics in functional programming*. Reading MA: Addison-Wesley. pp. 17-42 (1990)

[508] Thomas P Hughes, The evolution of large technological systems. In: WE Bijker, TP Hughes, TJ Pinch, editors. *The social construction of technological systems*. Cambridge MA: MIT Press. pp. 51-82 (1987)

[509] Thomas P Hughes, *Human-built world: how to think about technology and culture*. Chicago: University of Chicago Press. (2004)

[510] Thomas P Hughes, *Rescuing Prometheus: four monumental projects that changed our world*. New York: Vintage Books. (2011)

[511] Thomas P. Hughes, The Dynamics of Technological Change: Salients, Critical Problems, and Industrial Revolutions. In: Giovanni Dosi, Renato Giannetti, Pier Angelo Toninelli, editors. *Technology and enterprise in a historical perspective*. Oxford: Clarendon Press. pp. 97-118 (1992)

[512] Thomas Parker Hughes, *Networks of power: electrification in Western society, 1880-1930*. Baltimore: Johns Hopkins University Press. (1993)

[513] Louis C Hunter, *Steamboats on the western rivers: an economic and technological history*. Camrbidge MA: Harvard University Press. (1949)

[514] A Hurlimann, S Dolnicar, When public opposition defeats alternative water projects: the case of Toowoomba Australia. *Water Research*, 44:1 287-297, (2010)

[515] Diane Hutchinson Australian Current GDP, GDP deflator, CPI, Population and Share Price Index: Data Sources and Methods. University of Sydney, (2012) http://www.measuringworth.com/datasets/australiadata/DataGuide.pdf

[516] IEA, *Technology Roadmap: Energy Storage*. Paris, France: International Energy Agency, (2014)

[517] IEEE, *Inter-operability*. New York, NY: Institute of Electrical and Electronics Engineers, (1990)

[518] IEEE, *IEEE Big Data for Advanced Manufacturing Workshop*, 14 July 2015, http://ieeebdam15.stanford.edu/

[519] Ivan Illich, *Tools for Conviviality*. Glasgow: Fontana/Collins. (1973)

[520] Illing, Kluh, *Spectrum Auctions and Competition in Telecommunications*. Cambridge, Massachusetts: The MIT Press. (2003)

[521] Milan Ilnyckyj, Anne Ahrens-Embleton, Jacqueline Allain, Lila Asher, Jody Chan, et al., *The fossil fuel industry and the case for divestment: update*. Toronto: Toronto350, (2015)

[522] Arlene Inouye, Charles Süsskind, Technological Trends and National Policy, 1937: The First Modern Technology Assessment. *Technology and Culture*, 18:4 593-621, (1977)

[523] International Atomic Energy Agency, *Thorium fuel cycle — potential benefits and challenges*. Vienna: International Atomic Energy Agency, (2005)

[524] Interservice Technological Forecasting Methodology Study Group, *Report on technological forecasting*. US Army Materiel Command, Department of the Navy: Navy Material Command, Air Force Systems Command, (1967)

[525] Ipsos, *Community Attitudes Towards Emerging Technology Issues - Biotechnology*. Department of Industry, Innovation, Science, Research and Tertiary Education, (2013)

[526] Ipsos, *Community Atttiudes Towards Emerging Technology Issues - Nanotechnology*. Dept of Industry, Innovation, Science, Research and Tertiary Education, (2013)

[527] Simon Jackson, The 'stump-jumpers': national identity and the mythology of Australian industrial design in the period 1930-1975. *Design Issues*, 18:4 14-23, (2002)

[528] Simon Jackson, Sacred Objects—Australian Design and National Celebrations. *Journal of Design History*, 19:3 249-255, (2006)

[529] Adam B Jaffe, Manuel Trajtenberg, Rebecca Henderson, Geographic localization of knowledge spillovers as evidenced by patent citations. *Quarterly Journal of Economics*, 108:3 577-598, (1993)

[530] Leo Janos, BR Rich Skunk Works: A Personal Memoir of My Years at Lockheed. Boston, MA: Back Bay Books (1996)

[531] Erich Jantsch, *Technological forecasting in perspective: a framework for technological forecasting, its techniques and organisation*. Paris: OECD. (1967)

[532] Richard Jarrett, Xun Guo Lin, Mark Westcott, *CSIRO risk profile analysis: guidance for the Home Insulation Safety Program*. Glen Osmond: CSIRO, (2011) https://web.archive.org/web/20110601102703/http://www.climatechange.gov.au/government/programs-and-rebates/hisp/reports/~/media/publications/hisp/csiro-report-hisp-2011.pdf

[533] John Jewkes, David Sawers, Richard Stillerman, *The sources of invention*. London: Macmillan. (1969)

[534] Brian David Johnson, Introduction: How to change the future. In: Cory Doctorow, will.i.am, Douglas Rushkoff, Brian David Johnson, editors. *The Tomorrow Project anthology: conversations about the future*: Richard Bowles (2011)

[535] Brian David Johnson, *Science fiction prototyping: designing the future with science fiction*: Morgan & Claypool Publishers. (2011)

[536] Lawrence A.S. Johnson, Rainbow's End: The quest for an optimal taxonomy. *Proceedings of the Linnean Society of New South Wales*, 93:1 8-45, (1968)

[537] William R Johnston, *Statistics on terrorism*, http://www.johnstonsarchive.net/terrorism/intlterror.html

[538] A Jones Absorbing Innovation by Australian Enterprises: The Role of Absorptive Capacity. Department of Industry, Tourism and Resources, (2008)

[539] Boyan Jovanovic, Peter L. Rousseau, General Purpose Technologies. In: Philippe Aghion, Steven N. Durlauf, editors. *Handbook of Economic Growth*. Amsterdam: Elsevier. pp. 1182-1207 (2005)

[540] Katrina Jungnickel From Frankenstein to the Roomba: The changing nature and socio-cultural meanings of robots and automation. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2015) http://acola.org.au/index.php/new-technologies-contributing-reports

[541] Katrina Jungnickel Printing the future? An analysis of the hype and hope of rapid prototyping technology. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2015) http://acola.org.au/index.php/new-technologies-contributing-reports

[542] Katrina Jungnickel Tinkering with technology: Examining past practices and imagined futures. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2015) http://acola.org.au/index.php/new-technologies-contributing-reports

[543] Dan M Kahan, Donald Braman, Paul Slovic, John Gastil, Geoffrey Cohen, Cultural cognition of the risks and benefits of nanotechnology. *Nature Nanotechnology*, 4:2 87-90, (2008)

[544] Dan M. Kahan, Donald Braman, Geoffrey L. Cohen, John Gastil, Paul Slovic, Who Fears the HPV Vaccine, Who Doesn't, and Why? An Experimental Study of the Mechanisms of Cultural Cognition. *Law and Human Behaviour*, 34501-516, (2010)

[545] Daniel Kahneman, *Thinking, fast and slow*. London: Penguin Books. (2011)

[546] Daniel Kahneman, Dan Lovallo, Timid choices and bold forecasts: a cognitive perspective on risk taking. In: Daniel Kahneman, Amos Tversky, editors. *Choices, Values, and Frames*. Cambridge: Cambridge University Press (2000)

[547] Daniel Kahneman, Dan Lovallo, Timid choices and bold forecasts: a cognitive perspective on risk taking. *Management Science*, 39:1 17-31, (1993)

[548] Daniel Kahneman, Ilana Ritov, David Schkade, Economic Preferences or Attitude Expressions? An Analysis of Dollar Responses to Public Issues. In: Daniel Kahneman, Amos Tversky, editors. *Choices, Values, and Frames*. Cambridge: Cambridge University Press (2000)

[549] Daniel Kahneman, Amos Tversky, On the psychology of prediction. *Psychological Review*, 80:4 237-251, (1973)

[550] Michio Kaku, *Physics of the future: how science will shape human destiny and our daily lives by the year 2100*. London: Penguin Books. (2011)

[551] Jonathan Karl, Climate change a greater threat than terrorism, White House says, 10 February 2015, http://abcnews.go.com/Politics/climate-change-greater-threat-terrorism-white-house/story?id=28872778

[552] Niklas Karlsson, George Loewenstein, Jane McCafferty, The economics of meaning. *Nordic Journal of Political Economy*, 30:1 61-75, (2004)

[553] Lynn A Karoloy, Constantijn W A Panis, *The 21st Century at Work: Forces Shaping the Future Workforce and Workplace in the United States*. RAND Corporation, (2004)

[554] Jane Holtz Kay, *Asphalt Nation: How the automobile took over America, and how we can take it back*. London: University of California Press. (1997)

[555] Michael Keating, Pressures for change. In: M Keating, G Davis, editors. *The future of governance*. St Leonards NSW: Allen & Unwin. pp. 8-40 (2000)

[556] Michael Keating, *Who rules? How government retains control of a privatised economy*. Sydney: Federation Press. (2004)

[557] John Keegan, *The face of battle: a study of Agincourt, Waterloo, and the Somme*. New York: Penguin Group US. (1983)

[558] Brandon Keim, *Did cars save our cities from horses? Debating a modern parable about waste and technology*, http://nautil.us/issue/7/waste/did-cars-save-our-cities-from-horses, 2013

[559] Patrick Kelly, Melvin Kranzberg, *Technological innovation: A critical review of current knowledge*: San Francisco Press San Francisco. (1978)

[560] Jeffrey R Kenworthy, Felix B Laube, Automobile dependence in cities: an international comparison of urban transport and land use patterns with implications for sustainability. *Environmental Impact Assessment Review*, 16:4 279-308, (1996)

[561] William R Kerr, Ramana Nanda, Matthew Rhodes-Kropf, Entrepreneurship as experimentation. *Journal of Economic Perspectives*, 28:3 25–48, (2014)

[562] Pushker A Kharecha, James E Hansen, Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. *Environmental Science & Technology*, (2013)

[563] Vinod Khosla Failure as a tool. (2013) http://www.khoslaventures.com/failure-as-a-tool

[564] Byoung Soo Kim, Measuring technological change – concept, method and implications In: Aurora AS Teixeira, editor. *Technological change*. Rijeka, Croatia: InTech. pp. 89-102 (2012)

[565] Stephen P. King, Twenty-first Colin Clark lecture: November 2011 Competition regulation in Australia: A report card. *Economic Analysis and Policy*, 42:1 17-35, (2012)

[566] N Stephan Kinsella, Against intellectual property. *Journal of Libertarian Studies*, 15:2 1-54, (2001)

[567] Eli Kintisch, Congress cancels contentious program to bolster industry. *Science*, 314752-753, (2006)

[568] Laszlo Kish, Robert D Nevels, *Twisted radio waves and twisted thermodynamics*, http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0056086, 2013

[569] Tine Kleif, Wendy Faulkner, "I'm No Athlete [but] I Can Make This Thing Dance!" - Men's Pleasure in Technology. *Science, Technology & Human Values*, 28:2 296-325, (2003)

[570] Burton H Klein, *Dynamic economics*. Cambridge MA: Harvard University Press. (1977)

[571] Trevor A Kletz, *What went wrong?: case histories of process plant disasters and how they could have been avoided*. Burlington MA: Gulf Professional Publishing. (2009)

[572] Ronald Kline, Trevor Pinch, Users as Agents of Technological Change: The social construction of the automobile in the rural United States. *Technology and Culture*, 37:4 763-795, (1996)

[573] Stephen J. Kline, Nathan Rosenberg, An Overview of Innovation. In: Ralph Landau, Nathan Rosenberg, editors. *The positive sum strategy: harnessing technology for economic growth*. Washington DC: National Academies Press. pp. 275-305 (1986)

[574] Lars Klüver, Michael Nentwich, Walter Peissl, Helge Torgersen, Fritz Gloede, et al., *European Participatory Technology Assessment - Participatory Methods in Technology Assessment and Technology Decision -Making*. (1999) http://www.tekno.dk/?lang=en

[575] Frank H Knight, *Risk, uncertainty, and profit*. Boston MA: Houghton Mifflin. (1921)

[576] Will Knight Proceed with Caution toward the Self-Driving Car. MIT Technology Review, (2013) http://www.technologyreview.com/review/513531/proceed-with-caution-toward-the-self-driving-car/

[577] Paul Kominers, *Interoperability case study: Internet of Things (IoT)*. Cambridge MA: Berkman Center for Internet & Society Research Publication Series, (2012) http://cyber.law.harvard.edu/publications

[578] Kati Korhonen-Yrjänheikki, Future of the Finnish engineering education: a collaborative stakeholder approach. Aalto: Aalto University, (2010)

[579] Gabor T Kovacs, Gary Morgan, E Carl Wood, Catherine Forbes, Donna Howlett, Community attitudes to assisted reproductive technology: a 20-year trend. *Medical Journal of Australia*, 179:10 536-538, (2003)

[580] Sylvia Kraemer, *Science and technology policy in the United States: Open systems in action*: Rutgers University Press. (2006)

[581] I. Kral Plugged in: Remote Australian Indigenous Youth and Digital Culture. Canberra: ANU College of Arts & Social Sciences, (2010)

[582] Melvin Kranzberg, Carroll W Pursell, *Technology in Western Civilization. Vol. 2. Technology in the Twentieth Century*; PJ Grogan, D F Kaiser, editors. New York: Oxford University Press. (1967)

[583] Donald B Kraybill, Karen M Johnson-Weiner, Steven M Nolt, *The Amish*. Maryland: John Hopkins University Press. (2013)

[584] Ken Krechmer, Open standards: definition and policy. In: Laura DeNardis, editor. *Opening standards: the global politics of interoperability*. Cambridge MA: MIT Press. pp. 219-237 (2011)

[585] Florian Kreuchauff, Nina Teichert, *Nanotechnology as general purpose technology*. Karlsruhe: Karlsruher Institut für Technologie, (2014)

[586] Krewitt, External costs of energy—Do the answers match the questions?: Looking back at 10 years of ExternE. *Energy Policy*, 30:10 839-848, (2002)

[587] Alfred L Kroeber, *Anthropology*: Harcourt Brace and Company. (1948)

[588] Alfred Louis Kroeber, Clyde Kluckhohn Culture: A critical review of concepts and definitions. Papers Peabody Museum of Archaeology & Ethnology: Harvard University, (1952)

[589] Brenden Kuerbis, Milton Mueller, Securing the root. In: Laura DeNardis, editor. *Opening standards: the global politics of interoperability*: MIT Press. pp. 45-62 (2011)

[590] Kunreuther, Managing hazardous waste: past, present and future. *Risk analysis*:11 19-26, (1991)

[591] James Howard Kunstler, *The long emergency: surviving the converging catastrophes of the twenty-first century*. New York: Atlantic Monthly Press. (2005)

[592] Osmo Kuusi, *Expertise in the future use of generic technologies - Epistemic and Methodological Considerations Concerning Delphi Studies*. Helsinki: Valtion taloudellinen tutkimuskeskus, Govemment Institute for Economic Research, (1999)

[593] Simon Kuznets, Inventive activity: problems of definition and measurement. *The rate and direction of inventive activity: economic and social factors*. Princeton NJ: NBER. pp. 19-51 (1962)

[594] Simon Kuznets, Modern economic growth: findings and reflections. *The American Economic Review*, 247-258, (1973)

[595] Yevgeny Kuznetsov, Charles Sabel, New open economy industrial policy: making choices without picking winners. *Economic Policy PREMnotes*, 161, (2011)

[596] Martin LaMonica, Three Schemes to Revolutionize Nuclear Power. *IEEE Spectrum*, (2015) http://spectrum.ieee.org/energy/nuclear/three-schemes-to-revolutionize-nuclear-power

[597] Ralph Landau, Nathan Rosenberg, *The positive sum strategy: harnessing technology for economic growth*. Washington DC: National Academies Press. (1986)

[598] David S Landes, *The unbound Prometheus: technological change and industrial development in Western Europe from 1750 to the present*: Cambridge University Press. (2003)

[599] RN Langlois, Modularity in technology, organization, and society. *Journal of Economic Behavior & Organization*, 49:1 19-37, (2002)

[600] Edwin T Jr Layton, Technology as knowledge. *Technology and culture*, 15:1 31-41, (1974)

[601] Melissa Leach, Ian Scoones, Brian Wynne, *Science and citizens: globalization and the challenge of engagement*. London: Zed Books. (2005)

[602] Lucian L Leape, Error in medicine. *JAMA*, 272:23 1851-1857, (1994)

[603] Neal Leavitt Israeli Semiconductor Industry Continues to Thrive, but Some Clouds May Be on Horizon. Computing Now, (2014) http://www.computer.org/web/nealnotes/content?g=7989281&type=blogpost&urlTitle=israeli-semiconductor-industry-continues-to-thrive-but-some-clouds-may-be-on-horizon

[604] Hokyu Lee, Retrospective technology assessment: the impacts of computer communications on the structure of the public telephone network. *Telecommunications Policy*, 21:9/10 845-859, (1997)

[605] Robert J Lempert, Steven W Popper, Steven C Bankes, *Shaping the next one hundred years: new methods for quantitative, long-term policy analysis*. Santa Monica CA: Rand Corporation. (2003)

[606] Lens, *Open public resource for innovation cartography*, April 2015, https://http://www.lens.org/lens/

[607] Josh Lerner, *Boulevard of broken dreams: why public efforts to boost entrepreneurship and venture capital have failed—and what to do about it*: Princeton University Press. (2009)

[608] Francois Leveque, *Transport Pricing of Electricity Networks*. Boston: Springer Science+Business Media Dordecht. (2003)

[609] Claude Lévi-Strauss, *The savage mind*: University of Chicago Press. (1966)

[610] Richard C Levin, Alvin K Klevorick, Richard R Nelson, Sidney G Winter, Appropriating the returns from industrial research and development. *Brookings Papers on Economic Activity*, 3783-831, (1987)

[611] Mark Levinson, *The box: how the shipping container made the world smaller and the world economy bigger*. Princeton NJ: Princeton University Press. (2006)

[612] Daniel A. Levinthal, The slow pace of rapid technological change: gradualism and punctuation in technological change. *Industrial and Corporate Change*, 7:2 217-247, (1998)

[613] Levitt Ruth The challenges of evidence provocation paper for the alliance for useful evidence, nesta. Alliance for useful information (2013)

[614] Steven D Levitt, John A List, *Field experiments in economics: the past, the present, and the future*. Cambridge MA: National Bureau of Economic Research, (2008) http://www.nber.org/papers/w14356

[615] Library and Archives Canada, *Made in Canada: Patents of Invention and the Story of Canadian Innovation*, 13 Februrary 2015, https://http://www.collectionscanada.gc.ca/innovations/index-e.html

[616] EA Life, Ray Wild, The development of creative engineers. *Oxford Review of Education*, 7:1 3-9, (1981)

[617] Sam Lilley, *Men, machines and history: a short history of tools and machines in relation to social progress*: Cobbett Press. (1948)

[618] Jessa Lingel, Tim Regan "It's in your Spinal Cord, It's in Your Fingertips": Practices of Craft in Building Software. CSCW 2014 - Craft, Repair, and DIY. Baltimore, MD, (2014)

[619] Albert N Link, Donald S Siegel, *Innovation, entrepreneurship, and technological change*. Oxford: University of Oxford, (2007)

[620] Kenneth Lipartito, Picturephone and the information age: the social meaning of failure. *Technology and Culture*, 44:1 50-81, (2003)

[621] Richard G Lipsey, Cliff Bekar, Kenneth Carlaw, What requires explanation? In: E Helpman, editor. *General purpose technologies and economic growth*. Cambridge: MA: MIT Press. pp. 14-54 (1998)

[622] Richard G Lipsey, Kenneth I Carlaw, Clifford T Bekar, *Economic transformations: general purpose technologies and long-term economic growth*. Oxford: Oxford University Press. (2005)

[623] Robert E Litan, Andrew W Wyckoff, Kaye Husbands Fealing, *Capturing change in science, technology, and innovation: improving indicators to inform policy*. National Academies Press, (2014)

[624] Todd Litman, *Autonomous Vehicle Implementation Prediction: Implications for Transport Planning*. Victoria Transport Policy Institute, (2013)

[625] Susana Llorens, Marisa Salanova, Rosa Grau, Training to Technological Change. *Journal of Research on Technology in Education*, 35:2 206-212, (2002-03)

[626] Christoph H. Loch, Bernardo A. Huberman, A punctuated-equilibrium model of technology diffusion. *Management Science*, 45:2 160-177, (1999)

[627] Benjamin B Lockwood, Charles G Nathanson, E Glen Weyl Taxation and the allocation of talent. Harvard University, (2013)

[628] George Loewenstein, The psychology of curiosity: A review and reinterpretation. *Psychological bulletin*, 116:1 75-98, (1994)

[629] George Loewenstein, Drazen Prelec, Anomalies in Intertemporal Choice: Evidence and an Interpretation. *The Quarterly Journal of Economics*, 107:2 573-597, (1992)

[630] V Lohsoonthorn, S Lertmaharit, MA Williams, Prevalence of metabolic syndrome among professional and office workers in Bangkok, Thailand. *Journal of the Medical Association of Thailand*, 90:9 1908-1915, (2007)

[631] Dan Lovallo, Daniel Kahneman, Delusions of success: how optimism undermines executives' decisions. *Harvard Business Review*, (2003)

[632] Bryan R. Luce, Anne Elixhauser, Estimating costs in the economic evaluation of medical technologies. *International Journal of Technology Assessment In Health Care*, 657-75, (1990)

[633] Kate Lundy, *Pair Gains System: 2009 update*, April 2015, https://web.archive.org/web/20100220204138/http://www.katelundy.com.au/2009/10/18/pair-gains-2009-update/

[634] John Lydon, David Dyer, Chris Bradley, *Compete to prosper: improving Australia's global competitiveness*. McKinsey Australia, (2014)

[635] Kevin Lynch, *What time is this place?* Cambridge MA MIT Press. (1976)

[636] John Lyons, Richard Chait, Jordan Willcox, *An assessment of the science and technology predictions in the Army's STAR21 report*. Washington DC: Center for Technology and National Security Policy, National Defense University, (2008)

[637] Alan MacCormack, John Rusnak, Carliss Baldwin Exploring the duality between product and organizational architectures: a test of the "mirroring" hypothesis. Working Papers. Cambridge MA: Harvard Business School, (2008)

[638] Donald MacKenzie, *Knowing machines: essays on technical change*. Cambridge MA: MIT Press. (1996)

[639] Roy MacLeod, Colonial engineers and the 'cult of practicality': Themes and dimensions in the history of Australian engineering. *History and Technology: An International Journal*, 12:2 147-162, (1995)

[640] Norman Macrae, *The 2025 report: a concise history of the future, 1975-2025*. New York: Macmillan Publishing Co. (1984)

[641] Alexis C Madrigal, *#BostonBombing: the anatomy of a misinformation disaster*, http://www.theatlantic.com/technology/archive/2013/04/-bostonbombing-the-anatomy-of-a-misinformation-disaster/275155/, 2013

[642] Lutz Mailänder Presentation, Topic 1: Patent landscaping, mapping & analytics. World Intellectual Property Organization. Manila, http://www.wipo.int/edocs/mdocs/mdocs/en/wipo_ip_mnl_13/wipo_ip_mnl_13_1.pdf

[643] James Manyika, Michael Chui, Brad Brown, Jacques Bughin, Richard Dobbs, et al., *Big data: the next frontier for innovation, competition, and productivity*. McKinsey Global Institute, (2011)

[644] James Manyika, Michael Chui, Jacques Bughin, Richard Dobbs, Peter Bisson, et al., *Disruptive technologies: advances that will transform life, business, and the global economy*. McKinsey Global Institute, (2013)

[645] James Manyika, Jeff Sinclair, Richard Dobbs, Gernot Strube, Louis Rassey, et al., *Manufacturing the future: the next era of global growth and innovation*. McKinsey Global Institute and McKinsey Operations Practice, (2012)

[646] C. Marchetti, A Postmortem Technology Assessment of the Spinning Wheel: The Last Thousand Years. *Technological Forecasting & Social Change*, 1391-93, (1979)

[647] Marchment Hill Consulting, *Energy Storage in Australia: Commercial Opportunities, Barriers and Policy Options*. Clean Energy Council, (2012)

[648] Simon Marginson, Russell Tytler, Brigid Freeman, Kelly Roberts, *STEM: Country Comparisons*. Australian Council of Learned Academies, (2013) http://www.acola.org.au/PDF/SAF02Consultants/SAF02_STEM_FINAL.pdf

[649] David Marsh, Stability and change: the last dualism? *Critical Policy Studies*, 4:1 86-101, (2010)

[650] Mike W Martin, Personal meaning and ethics in engineering. *Science and Engineering Ethics*, 8545-560, (2002)

[651] Sylvia Libow Martinez, Gary Stager, *Invent to learn: making, tinkering, and engineering in the classroom*. Torrance CA: Constructing Modern Knowledge Press. (2013)

[652] Carolyn Marvin, When old technologies were new: implementing the future. In: H Mackay, T O'Sullivan, editors. *The media reader: continuity and transformation*. New York: Sage Publications (1999)

[653] Leo Marx, Technology: The Emergence of a Hazardous Concept. *Social Research*, 965-988, (1997)

[654] Mark Matthews, Capability building and risk management: Lessons from Radiata. *Innovation: Management, Policy & Practice*, 9:2 170-180, (2007) http://dx.doi.org/10.5172/impp.2007.9.2.170

[655] Mark Matthews, Bob Frater Creating and Exploiting Intangible Networks: How Radiata was able to improve its odds of success in the risky process of innovating. Occasional Paper No 1/13. Melbourne: Intellectual Property Research Institute of Australia, (2013)

[656] Graham H. May, *The future is ours: foreseeing, managing and creating the future*. Westport CT: Praeger (1996)

[657] Viktor Mayer-Schönberger, Kenneth Cukier, *Big data: a revolution that will transform how we live, work, and think*. New York: Houghton Mifflin Harcourt. (2013)

[658] Deborah G Mayo, *Error and the growth of experimental knowledge*. Chicago: University of Chicago Press. (1996)

[659] Otto Mayr, *The origins of feedback control*: The MIT Press (1975)

[660] Melissa Mazmanian, Wanda J Orlikowski, JoAnne Yates, The autonomy paradox: the implications of mobile email devices for knowledge professionals. *Organization Science*, 24:5 1225-1250, (2013)

[661] Edward G. Mazurs, *Graphical Representations of the Periodic System During One Hundred Years*: The University of Alabama Press. (1957)

[662] Mariana Mazzucato, *The entrepreneurial state: debunking public vs. private sector myths*. London: Anthem Press. (2013)

[663] John McCarthy, Peter Wright, *Technology as experience*. Cambridge: MIT Press. (2004)

[664] Brandon McFadden, Jayson Lusk Cognitive Biases in the Assimilation of Scientific Information on Global Warming and Genetically Modified Food. Southern Agricultural Economics Association 2014 Annual Meeting. Dallas, Texas: AgEcon, (2014) http://purl.umn.edu/162532

[665] John O McGinnis, *Accelerating Democracy: Transforming Governance Through Technology*. Princeton: Princeton University Press. (2012)

[666] Donald W McKinnon, Intellect and motive in scientific inventors: implications for supply. In: National Bureau of Eonomic Research, editor. *The rate and direction of inventive activity: economic and social factors*: Princeton University Press. pp. 361-384 (1962)

[667] McKinsey & Company, *Ten IT-enabled business trends for the decade ahead*. McKinsey Global Institute, (2013)

[668] McKinsey Global Institute, *Internet matters: the Net's sweeping impact on growth, jobs and prosperity*. McKinsey and Company, (2011)

[669] Marilynn McLachlan Nine inventions by talented New Zealanders. The New Zealand Herald, (2014) http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=11248438

[670] Ian W McLean, *Why Australia prospered: the shifting sources of economic growth*: Princeton University Press. (2012)

[671] John McMillan, *Reinventing the bazaar: A natural history of markets*. New York: W.W Norton & Company. (2002)

[672] JR McNeill, *Something new under the sun: an environmental history of the twentieth century*. London: Penguin. (2000)

[673] Ralf R Meisenzahl, Joel Mokyr, The Rate and Direction of Invention in the British Industrial Revolution: Incentives and institutions. In: Josh Lerner, Scott Stern, editors. *The Rate and Direction of Inventive Activity Revisited*: University of Chicago Press. pp. 443-479 (2011)

[674] Marc W Melaina, Turn of the century refueling: A review of innovations in early gasoline refueling methods and analogies for hydrogen. *Energy Policy*, 35:10 4919-4934, (2007)

[675] David Mercer, *The telephone: the life story of a technology*. Westport CT: Greenwood Press. (2006)

[676] R. N. Mercken, IT Investment Decisions: Value, Uncertainty and Gut Feeling. *Tijdschrift voor Economie en Management*, L:4, (2005)

[677] Robert P Merges, *Justifying intellectual property*: Harvard University Press. (2011)

[678] Tracy Merlin, Skye Newton, Benjamin Ellery, Joanne Milverton, Claude Farah, *Systematic review of the human health effects of wind farms*. Canberra: National Health and Medical Research Council, (2013) http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh54_systematic_review_of_the_human_health_effects_of_wind_farms_december_2013.pdf

[679] Stephen A Merrill, Anne-Marie Mazza, editors *Managing University Intellectual Property in the Public Interest* Washington DC: National Academy Press. (2010)

[680] RK Merton, Singletons and multiples in scientific uncertainty. *Proceedings of the American Philosophical Society*, 105:5 470-486, (1961)

[681] Robert K Merton, The self-fulfilling prophecy. *Antioch Review*, 8:2 193-210, (1948)

[682] Robert K Merton, *The sociology of science: theoretical and empirical investigations*. Chicago: University of Chicago Press. (1973)

[683] Robert K Merton, Elinor Barber, *The travels and adventures of serendipity: A study in sociological semantics and the sociology of science*: Princeton University Press. (2006)

[684] Alex Mesoudi, *Cultural evolution: how Darwinian theory can explain human culture and synthesize the social sciences*: University of Chicago Press. (2011)

[685] DG Messerschmitt, Rethinking components: from hardware and software to systems. *Proceedings of the IEEE*, 95:7 1473 - 1496, (2007)

[686] J Stanley Metcalfe, *Evolutionary economics and creative destruction*. London, New York: Routledge. (1998)

[687] J.S. Metcalfe, Technology systems and technology policy in an evolutionary framework. *Cambridge Journal of Economics*, 19:25-46, (1995)

[688] JS Metcalfe, Ian Miles, Standards, selection and variety: an evolutionary approach. *Information Economics and Policy*, 6243-268, (1994)

[689] Microsoft, *Overview of the .NET Framework*, https://msdn.microsoft.com/en-us/library/zw4w595w.aspx

[690] Stephen B Miles, Sanjay E Sarma, John R Williams, editors *RFID technology and applications*. Cambridge: Cambridge University Press. (2008)

[691] Katherine L Milkman, Dolly Chugh, Max H Bazerman, How can decision making be improved? *Perspectives on Psychological Science*, 4:4 379-383, (2009)

[692] Steve Miller, Public understanding of science at the crossroads. *Public Understanding of Science*, 10:1 115-120, (2001)

[693] John Mills, Australia's mixed gauge railway system: a reassessment of its origins *Journal of the Royal Australian Historical Society* 96:1 50-61, (2010) http://search.informit.com.au/documentSummary;dn=201006632;res=IELAPA

[694] John Ayres Mills, The myth of the standard gauge: rail gauge choice in Australia 1850-1901: Griffith University, (2006)

[695] Alberto E Minetti, John Pinkerton, Paola Zamparo, From bipedalism to bicyclism: evolution in energetics and biomechanics of historic bicycles. *Proceedings of the Royal Society of London B: Biological Sciences*, 268:1474 1351-1360, (2001)

[696] EJ Mishan, Euston Quah, *Cost–benefit analysis*. London: Routledge. (2007)

[697] Carl Mitcham, *Thinking through technology: The path between engineering and philosophy*: University of Chicago Press. (1994)

[698] Sandra D Mitchell, *Unsimple truths: science, complexity, and policy*. Chicago: University of Chicago Press. (2009)

[699] William J Mitchell, *Reinventing the automobile: Personal urban mobility for the 21st century*: MIT press. (2010)

[700] Espen Moe, Structural Change, Vested Interests, and Scandinavian Energy Policy-Making: Why Wind Power Struggles in Norway and not in Denmark. *The Open Renewable Energy Journal*, 519-31, (2012)

[701] S. Moein Moghimi, A. Christy Hunter, J. Clifford Murray, Nanomedicine: current status and future prospects. *FASEB Journal*, 19311-330, (2005)

[702] Hazel VJ Moir, Do Patent Systems Improve Economic Well-Being? An Exploration of the Inventiveness of Business Method Patents. Canberra: Australian National University, (2010)

[703] Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress*. New York: Oxford University Press. (1990)

[704] Joel Mokyr, Punctuated equilibria and technological progress. *American Economic Review*, 80:2 350-354, (1990)

[705] Joel Mokyr, Evolutionary biology, technological change and economic history. *Bulletin of Economic Research*, 43:2 127-149, (1991)

[706] Joel Mokyr, Technological inertia in economic history. *Journal of Economic History*, 52:2 325-338, (1992)

[707] Joel Mokyr, Cardwell's Law and the political economy of technological progress. *Research Policy*, 23:5 561-574, (1994)

[708] Joel Mokyr Invention and rebellion: why do innovations occur at all? An evolutionary approach. Conference on minorities and economic growth. Bar Ilan University: Elsevier Publishers, Amsterdam. pp. 179-203, (1998)

[709] Joel Mokyr, Why "more work for mother?" Knowledge and household behavior, 1870–1945. *The Journal of Economic History*, 60:01 1-41, (2000)

[710] Joel Mokyr, *The gifts of Athena: historical origins of the knowledge economy*. Princeton: Princeton University Press. (2002)

[711] Joel Mokyr, Long-term economic growth and the history of technology. *Handbook of Economic Growth*, 11113-1180, (2005)

[712] Joel Mokyr, Chris Vickers, Nicolas L Ziebarth Technological Anxiety and the Future of Economic Growth: Is this time different? ,

[713] Enid N.H. Montague, Brian M.Kleiner, Woodrow W. Winchester III, Emprically understanding trust in medical technology. *International Journal of Industrial Ergonomics*, 39:4 1-7, (2009)

[714] Monument Australia, *Fluoride Memorial*, http://monumentaustralia.org.au/themes/culture/social/display/70032-fluoride-memorial/photo/1, 2010

[715] Gordon E Moore, Cramming more components onto integrated circuits. *Electronics*, 38:8 114–117, (1965) http://www.monolithic3d.com/uploads/6/0/5/5/6055488/gordon_moore_1965_article.pdf

[716] Seana Moran, The roles of creativity in society. In: James C Kaufman, Robert J Sternberg editors. *The Cambridge Handbook of Creativity*. Cambridge: Cambridge University Press (2010)

[717] Carey K. Morewedge, Daniel T. Gilbert, Timothy D. Wilson, The least likely of times: how remembering the past biases forecasts of the future. *Psychological Science*, 16:8 626-630, (2005)

[718] Eric Morris, *From horse power to horsepower*, http://www.uctc.net/access/30/Access 30 - 02 - Horse Power.pdf, 2007

[719] Petra Moser, *How do patent laws influence innovation? Evidence from nineteenth-century world fairs*. National Bureau of Economic Research, (2003)

[720] Petra Moser, Patents and Innovation: Evidence from Economic History. *The Journal of Economic Perspectives*, 27:1 23-44, (2013)

[721] Moses L B, Adapting the Law to Technological Change: A Comparison of Common Law and Legislation. *UNSWLJ*, 26394, (2003)

[722] Moses L B, Agents of Change: How the Law Copes with Technological Change. *Griffith L Rev*, 20763, (2011)

[723] Lyria Bennett Moses, Recurring dilemmas: the law's race to keep up with technological change. *Journal of Law, Technology and Policy*, 2007:2 239-285, (2007)

[724] Lyria Bennett Moses, Understanding legal responses to technological change of in vitro fertilization *Minnesota Journal of Science and Technology*, 6:2 506-618, (2007) http://mjlst.umn.edu/prod/groups/ahc/@pub/@ahc/@mjlst/documents/asset/ahc_asset_365920.pdf

[725] Lyria Bennett Moses, Agents of Change: How the Law Copes with Technological Change. *Griffith L Rev*, 20763, (2011)

[726] Nick Mouter, Cost benefit analysis in practice. Netherlands: Netherlands National University, (2014)

[727] David C Mowery, Nathan Rosenberg, *Technology and the pursuit of economic growth*. Cambridge: Cambridge University Press. (1991)

[728] Ann Moyal, Invention and innovation in Australia: the historian's lens. *Prometheus: Critical Studies in Innovation*, 5:1 92-110, (1987)

[729] Ann Moyal, The gendered use of the telephone: an Australian case study. *Media, Culture & Society*, 14:1 51-72, (1992)

[730] Michael Muetzelfeldt, The Framework of Debate over Technological Change in Australia. *Public Administration*, 63:4 465-474, (1985)

[731] Peter Mulder, Carl H Reschke, René Kemp Evolutionary theorising on technological change and sustainable development. OCFEB Research Memorandum 9912, 'Environmental Policy, Economic Reform and Endogenous Technology', (1999)

[732] John Mullins, Randy Kosimar, *Getting to plan B: breaking through to a better business model*. Boston MA: Harvard Business Press. (2009)

[733] Lewis Mumford, *Technics and civilization*. London: George Routledge & Sons. (1946)

[734] Lewis Mumford, *The pentagon of power*. New York: Harcourt Brace Jovanovich. (1970)

[735] Natalie D Munro, Small game, the Younger Dryas, and the transition to agriculture in the southern Levant. *Mitteilungen der Gesellschaft für Urgeschichte* 47-71, (2003)

[736] Doyne Farmer J Nagy B, Bui Q. M., Trancik J. E., Statistical Basis for Predicting Technological Progress. *PloS one*, (2012)

[737] Sreeja Nair, Michael Howlett, *Dealing with the likelihood of failure over the long-term: adaptive policy design under uncertainty*. (2014)

[738] Roddam Narasimha, J Srinivasan, S.K Biswas, *The Dynamics of Technology: Creation and Diffusion of Skills and Knowledge*. New Dehli: Sage publications. (2003)

[739] National Academies, *Understanding the Formation of Attitudes to Nuclear Power in Australia*. National Academies, (2010)

[740] National Academy of Engineering, *Educating the engineer of 2020: adapting engineering education to the new century*. Washington DC: National Academies Press. (2005)

[741] National Academy of Engineering, *Messaging for engineering: from research to action*. Washington DC: National Academy of Engineering, (2013)

[742] National Academy of Sciences, *Continuing Innovation in Information Technology*. Washington DC: National Academy of Sciences. 42 p, (2012)

[743] National Research Council, *Continuing innovation in information technology*. Washington DC: National Academies Press, (2012) http://www.nap.edu/catalog.php?record_id=13427

[744] National Research Council (US), *Hidden Costs of Energy: Unpriced consequences of energy production and use*. Washington: The National Academies, (2010)

[745] National Resources Committee (Subcommittee on Technology), *Technological trends and national policy including the social implications of new inventions*. Washington: National Resources Committee, (1937)

[746] N Nayab, Kaizen: The key to Japan's competitive success. *Publications Oboulo com*, (2009)

[747] NBN Co, *Strategic Review*. Sydney, Australia, (2013)

[748] Colin Neagle, *A guide to the confusing Internet of Things standards world*, http://www.networkworld.com/article/2456421/internet-of-things/a-guide-to-the-confusing-internet-of-things-standards-world.html, 2014

[749] Rupert Neate, *Kodak falls in the 'creative destruction of the digital age'* http://www.theguardian.com/business/2012/jan/19/kodak-bankruptcy-protection, 2012

[750] Frederik Nebeker, *Dawn of the electronic age: electrical technologies in the shaping of the modern world, 1914-1945*. Piscataway NJ: IEEE Press, John Wiley. (2009)

[751] Dale Neef, G Anthony Siesfeld, Jacquelyn Cefola, editors *The economic impact of knowledge: resources for the knowledge-based economy*. Boston: Butterworth Heinemann. (1998)

[752] Andrew T. Nelson, Thorium: not a near-term commercial nuclear fuel. *Bulletin of the Atomic Scientists*, 68:5 33-44, (2012)

[753] Richard Nelson Introduction to "The Rate and Direction of Inventive Activity: Economic and Social Factors". National Bureau of Economic Research, (1962)

[754] Richard R Nelson, The simple economics of basic scientific research. *The Journal of Political Economy*, 67:3 297-306, (1959)

[755] Richard R Nelson, The co-evolution of technology, industrial structure, and supporting institutions. *Industrial and corporate change*, 3:1 47-63, (1994)

[756] Richard R Nelson, On the uneven evolution of human know-how. *Research Policy*, 32:6 909-922, (2003)

[757] Richard R Nelson, *Technology, institutions, and economic growth*. Cambridge MA: Harvard University Press. (2005)

[758] Richard R Nelson, Edmund S Phelps, Investment in Humans, Technological Diffusion, and Economic Growth. *American economic review*, 56:2, (1966)

[759] Richard R Nelson, Sidney G Winter, Herbert L Schuette, Technical change in an evolutionary model. *The Quarterly Journal of Economics*, 90:1 90-118, (1976)

[760] Richard R. Nelson, Sidney G. Winter, *An Evolutionary Theory of Economic Change*. Cambridge, Massachusetts: Belknap Press. (1982)

[761] David Nethercot, David Lloyd Smith, *Attracting the best and brightest: broadening the appeal of engineering education*. London: Ove Arup Foundation, (2001)

[762] CM Newman, JE Cohen, C Kipnis, Neo-darwinian evolution implies punctuated equilibria. *Nature*, 315:6018 400-401, (1985)

[763] Judith Newman To Siri, With Love. The New York Times, (2014) http://www.nytimes.com/2014/10/19/fashion/how-apples-siri-became-one-autistic-boys-bff.html?_r=2

[764] Michelle Nic Raghnaill Evolution of Education – How societal readiness and technological improvement is improving online higher education access and quality worldwide. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2014) http://acola.org.au/index.php/new-technologies-contributing-reports

[765] Michelle Nic Raghnaill Locked into the car: How a vision of unfettered transport freedom transformed personal mobility and reshaped the world. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2014) http://acola.org.au/index.php/new-technologies-contributing-reports

[766] NICTA, *Water pipe failure prediction*, http://www.nicta.com.au/content/uploads/2015/02/Water-Pipe-Failure-Prediction-vers2.pdf

[767] NICTA, *National Map*, http://nicta.github.io/nationalmap/public/info.html

[768] Michael A. Nielsen, Isaac L. Chuang, *Quantum computation and quantum information*. Cambridge: Cambridge University Press. (2010)

[769] Tuomo Nikulainen, Martti Kulvik How General are General Purpose Technologies: Evidence from nano-, bio- and ICT-technologies in Finland. Discussion paper 1208. Helsinki: Elinkeinoelaman Tutkimuslaitos: The Research Institute of the Finnish Economy (2009)

[770] David Nofre, Mark Priestley, Gerard Alberts, When Technology Became Language: The Origins of the Linguistic Conception of Computer Programming, 1950–1960. *Technology and Culture*, 55:1 40-75, (2014)

[771] Kari Marie Norgaard, *Living in denial: Climate change, emotions, and everyday life*: MIT Press. (2011)

[772] Donald A Norman, Roberto Verganti Incremental and radical innovation: design research versus technology and meaning change. Design Issues, (2012)

[773] Douglass C North, *Understanding the process of economic change*. Princeton and Oxford: Princeton University Press. (2006)

[774] Brendan Nyan, Jason Reifler, Sean Richey, Gary L. Freed, Effective Messages in Vaccine Promotion: A Randomized Trial. *Pediatrics*, (2014) http://pediatrics.aappublications.org/content/early/2014/02/25/peds.2013-2365

[775] David E Nye, *American technological sublime*. Cambridge: MIT Press. (1996)

[776] David E Nye, *Technology matters: questions to live with*. Cambridge MA: MIT Press. (2006)

[777] Tiffany O'Callaghan What we miss when we read on screens. New Scientist. pp. 41-43, (2014)

[778] Aidan O'Driscoll, Marius Claudy, Mark Peterson, Understanding the Attitude-Behavior Gap for Renewable Energy Systems Using Behavioral Reasoning Theory. *Journal of Macromarketing*, 33:4, (2013)

[779] Gerard K O'Neill, *2081: a hopeful view of the human future*. New York: Simon & Schuster. (1981)

[780] Tim O'Reilly, Gov 2.0: it's all about the platform, http://techcrunch.com/2009/09/04/gov-20-its-all-about-the-platform/

[781] Timothy O'Riordan, Political decisionmaking and scientific indeterminancy. In: Vincent T. Covello, Jeryl L. Mumpower, Pieter J.M. Stallen, V.R.R. Uppuluri, editors. *Environmental Impact Assessment, Technology Assessment, and Risk Analysis*. Berlin: Springer Verlag (1983)

[782] FJ Odling-Smee, KN Laland, MW Feldman, *Niche construction: the neglected process in evolution*: Princeton University Press. (2003)

[783] OECD, *Addressing the Economics of Waste*. Paris: OECD, (2004)

[784] OECD, *The Economic Impact of ICT: Measurement, Evidence and Implications*. Organisation for Economic Co-operation and Development, (2004)

[785] OECD, *Broadband and the economy*. OECD, (2008)

[786] OECD, *Performance-based funding for public research in tertiary education institutions: workshop proceedings*. OECD Publishing, (2010) http://www.oecd.org/sti/sci-tech/performance-basedfundingforpublicresearchintertiaryeducationinstitutionsworkshopproceedings.htm - HTO

[787] OECD, *OECD Science, Technology and Industry Scoreboard 2013*: OECD Publishing. (2013)

[788] OECD, *OECD Science, technology and Industry Outlook 2014*: OECD Publishing. (2014)

[789] Cabinet Office, Office of Cyber Security and Information Assurance, Department for Business Innovation & Skills, Foreign & Commonwealth Office, *Keeping the UK safe in cyberspace*. Gov.uk, (2014) https://http://www.gov.uk/government/policies/keeping-the-uk-safe-in-cyberspace

[790] Office of Technology Assessment Office of Technology Assessment Archive. http://ota.fas.org/

[791] Office of Technology Assessment, *The Technological Reshaping of Metroplolitan America*. Congress of the United States, (1995)

[792] William F Ogburn, S Colum Gilfillan, The influence of invention and discovery. *Research Committee on Social Trends: Recent social trends in the United States*: McGraw-Hill Book Company (1933)

[793] James Ogunleye, An investigation of curriculum arrangements conducive to fostering creativity in post-compulsory education and training institutions: University of Greenwich, (2002)

[794] Herbert Ohlman, Information: Timekeeping, Computing, Telecommunications and Audiovisual Technologies. In: Ian McNeil, editor. *An Encyclopaedia of the History of Technology*. London: Routledge (1990)

[795] Online Learning Consortium, *MOOCs in the community college: implications for innovation in the classroom*, http://olc.onlinelearningconsortium.org/conference/2013/blended/moocs-community-college-implications-innovation-classroom, 2013

[796] W Oremus Forget MOOCs. Slate, (2013) http://www.slate.com/articles/technology/technology/2013/09/spocs_small_private_online_classes_may_be_better_than_moocs.html

[797] Marju Orho-Melander, *The metabolic syndrome: genetics, lifestyle and ethnicity*, https://http://www.idf.org/sites/default/files/attachments/article_412_en.pdf, 2006

[798] Wanda J Orlikowski, Using technology and constituting structures: A practice lens for studying technology in organizations. *Resources, co-evolution and artifacts*: Springer. pp. 255-305 (2008)

[799] Kerri Jean Ormerod, Christopher A Scott, Drinking wastewater: public trust in potable reuse. *Science Technology & Human Values*, 38:3 351-373, (2013)

[800] Ingrid Ott, Nina Teichert, *Generality of purpose: linking creativity and technology*. evoREG Research Note, (2011)

[801] Nelly Oudshoorn, *The male pill: A biography of a technology in the making*: Duke University Press. (2003)

[802] P.C.Stubbs, Technological change in Australia: A review of the Myers Report. *The Economic Record*, 57224-231, (1981)

[803] Arnold Pacey, *The culture of technology*: MIT press. (1983)

[804] Arnold Pacey, *The maze of ingenuity: Ideas and idealism in the development of technology*: The MIT Press. (1992)

[805] Arnold Pacey, *Meaning in technology*. Cambridge MA: MIT Press. (2001)

[806] Pete Pachal, How Kodak squandered every single digital opportunity it had, 21 January 2012, http://mashable.com/2012/01/20/kodak-digital-missteps/

[807] Pete Pachal, *Why history is against Amazon's 3D phone*, http://mashable.com/2014/06/18/3d-phone-history/

[808] Miles J Padgett, Light's twist. *Proceedings of the Royal Society A*, 470, (2014)

[809] John Gorham Palfrey, Urs Gasser, *Interop: The promise and perils of highly interconnected systems*: Basic Books. (2012)

[810] John R Pani, Julia H Chariker, The psychology of error in relation to medical practice. *Journal of Surgical Oncology*, 88130-142, (2004)

[811] Govindan Parayil, Technological knowledge and technological change. *Technology in Society*, 13289-304, (1991)

[812] Rick Parente, Janet Anderson-Parente, A case study of long-term Delphi accuracy. *Technological Forecasting and Social Change*, 78:9 1705-1711, (2011)

[813] Eli Pariser, *The filter bubble: What the Internet is hiding from you*: Penguin. (2011)

[814] Alice Park, *Sitting is killing you*, http://time.com/sitting/, 2014

[815] DL Parnas, On the criteria to be used in decomposing systems into modules. *Communications of the Association for Computing Machinery*, 15:12, (1972)

[816] Eric Paulos You Amateur! Interactions: ACM. pp. 52-57, (2012)

[817] Cesare Pautasso, Erik Wild, Rosa Alarcon, editors *REST: advanced research topics and practical applications*. New York: Springer. (2014)

[818] Cesare Pautasso, Olaf Zimmermann, Frank Leymann RESTful web services vs. 'big' web services: making the right architectural decision. Beijing: International World Wide Web Conference Committee (IW3C2), (2008)

[819] PCAST PCAST Considers Massive Open Online Courses (MOOCs) and Related Technologies in Higher Education. (2013) https://http://www.whitehouse.gov/blog/2013/12/18/pcast-considers-massive-open-online-courses-moocs-and-related-technologies-higher-ed

[820] David Pearce, Giles Atkinson, Susana Mourato, *Cost-Benefit Analysis and the Environment: Recent Developments*. OECD, (2006)

[821] Warren Pearce, Sujatha Raman, The new randomised controlled trials (RCT) movement in public policy: challenges of epistemic governance. *Policy Sciences*, 47387–402, (2014)

[822] Carlota Perez The New Technologies: An integrated view. Working Papers in Technology Governance and Economic Dynamics: Tallinn University of Technology, (1986)

[823] Carlota Perez, *Technological revolutions and financial capital: the dynamics of bubbles and golden ages*. Cheltenham: Edward Elgar (2002)

[824] Carlota Perez, *The financial crisis and the future of innovation: A view of technical change with the aid of history*. TUT Ragnar Nurkse School of Innovation and Governance, (2010)

[825] Carlota Perez, Unleashing a golden age after the financial collapse: Drawing lessons from history. *Environmental Innovation and Societal Transitions*, 69-23, (2013)

[826] Carlota Perez, *Technological revolutions and techno-economic paradigms*. Tallinn University of Technology, (2009)

[827] Burt Perrin, How to - and how not to - evaluate innovation. *Evaluation*, 8:1 13-28, (2002)

[828] Charles Perrow, *Normal accidents: living with high-risk technologies*. USA: Basic Books. (1984)

[829] Walter L. Perry, Brian McInnis, Carter C. Price, Susan C. Smith, John S. Hollywood, *Predictive Policing: The Role of Crime Forecasting in Law Enforcement Operations*. Sanat Monica: RAND Corporation. (2013)

[830] Thomas J Peters, Robert H Jr Waterman, *In search of excellence: lessons from America's best-run companies*. New York: HarperCollins. (2004)

[831] Henry Petroski, *To engineer is human: the role of failure in successful design*. New York: Vintage Books. (1992)

[832] Henry Petroski, Shopping by design. *American Scientist*, 93:6 491-495, (2005)

[833] Henry Petroski, *Success through failure: the paradox of design*. Princeton NJ: Princeton University Press. (2006)

[834] Richard Pickersgill, *Dimensions of innovation: some historical perspectives on vocational education and training and innovation in Australia, a discussion paper*. Sydney: National Vocational Education and Training Research and Evaluation Program, (2005)

[835] Plato Phaedrus. http://www.perseus.tufts.edu/hopper/text?doc=Perseus%3Atext%3A1999.01.0174%3Atext%3DPhaedrus%3Apage%3D275

[836] John R Platt, Strong inference: proper scientific method (the New Baconians). *Science*, 146:3642 347-353, (1964)

[837] Barbara Pocock, Natalie Skinner, Morning, noon and night: The infiltration of work email into personal and family life. (2013)

[838] Michael Polanyi, *Personal Knowledge. Towards a Post Critical Philosophy*. London: Routledge. (1958)

[839] Sidney Pollard, *The idea of progress: history and society*. London: CA Watts and Co. (1968)

[840] Neil Pollock, Robin Williams, Technology choice and its performance: Towards a sociology of software package procurement. *Information and Organization*, 17131-161, (2007)

[841] Rosemary Polya, *Chronology of genetic engineering regulation in Australia: 1953-2008*, 21 July 2015, http://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/BN/0809/ChronGeneticEngineeringA

[842] Ithiel de Sola Pool, editor *The social impact of the telephone*. Cambridge MA: MIT Press. (1977)

[843] Ithiel de Sola Pool, *Forecasting the telephone: a retrospective technology assessment*. Norwood NJ: Ablex. (1983)

[844] Karl Popper, *The open society and it's enemies* London: Routledge. (1945)

[845] Karl Popper, editor *The logic of scientific discovery*. First published 1959 ed: Taylor & Francis. (2005)

[846] Karl R. Popper, Beyond the Search for Invariants, Essay 7. In: Arne F. Petersen, Jørgen Mejer, editors. *The World of Parmenides: Essays on the Presocratic Enlightenment*. London: Routledge (1998)

[847] Karl R. Popper, *The world of Parmenides: essays on the presocratic enlightenment*; Arne F. Petersen, Jørgen Mejer, editors. London: Routledge. (1998)

[848] Theodore M Porter, *Trust in numbers: the pursuit of objectivity in science and public life*. Princeton NJ: Princeton University Press. (1995)

[849] Neil Postman Informing ourselves to death. Stuttgart: German Informatics Society (Gesellschaft fur Informatik), (1990)

[850] Neil Postman, *Technopoly: the surrender of culture to technology*. New York: Vintage Books. (1993)

[851] Robert W Prehoda, *Designing the future*. Philadelphia: Chilton Book Co. (1967)

[852] Wolfgang F. E. Preiser, editor *Building Evaluation*. New York: Springer Science and Business Media. (1989)

[853] Wolfgang FE Preiser, JL Nasar, Assessing building performance: Its evolution from post-occupancy evaluation. *International Journal of Architectural Research*, 2:1 84-99, (2008)

[854] President's Council of Advisors on Science and Technology, *Designing a digital future: federally funded research and development in networking and information technology. Report to the President and Congress*. Executive Office of the US President, (2010)

[855] PricewaterhouseCoopers, Australian Industry Group, Australian Technology Network of Universities, *Innovate and Prosper: Ensuring Australia's Future Competitiveness through University-Industry Collaboration*. PricewaterhouseCoopers, Australian Industry Group, Australian Technology Network of Universities, (2015) http://apo.org.au/node/53950

[856] Robert Proctor, Londa L Schiebinger, *Agnotology: the making and unmaking of ignorance*. Stanford CA: Stanford University Press. (2008)

[857] Productivity Commission, *ICT use and productivity: A synthesis from studies of Australian firms*. Canberra: Productivity Commission. 1740371518 1740371518, (2004)

[858] PRoductivity Commission, *Public infrastructure: Productivity Commission Draft Report*. Melbourne, (2014)

[859] Productivity Commission, *Public infrastructure: Productivity Commission Draft Report vol 1*. Canberra, (2014)

[860] Douglas L Puffert, The standardization of track gauge on North American railways. *Journal of Economic History*, 60:4 933-960, (2000) http://www.jstor.org/stable/2698082

[861] Douglas L Puffert, Path dependence in spatial networks: the standardization of railway track gauge. *Explorations in Economic History*, 39:3 282-314, (2002)

[862] Robert Putnam, *Bowling alone: the collapse and revival of American community*. New York: Simon & Schuster. (2000)

[863] David Pye, *The nature and aesthetics of design*. London: Barrie and Jenkins. (1978)

[864] James Brian Quinn, Innovation and Corporate Strategy: Managed Chaos. *Technology in Society*:2-3 263-279, (1985)

[865] Quote Investigator, Quote Investigator: exploring the origins of quotations, http://quoteinvestigator.com/2012/09/27/invent-the-future/

[866] Amy Rabinowitz, Seongmin Lee, *Interoperability case study: mobile phone chargers*. (2012) http://cyber.law.harvard.edu/publications

[867] Matthew Raggatt, *Uber ride-sharing would be illegal in ACT*, http://www.canberratimes.com.au/act-news/uber-ridesharing-would-be-illegal-in-act-government-20141101-11fay4.html, 2014

[868] Michelle Nic Raghnaill, Robert C. Williamson Technology and work. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2014) http://acola.org.au/index.php/new-technologies-contributing-reports

[869] David Ramli 'Three strikes' anti-piracy scheme launched in wake of Dallas Buyers Club threat. The Sydney Morning Herald, (2015) http://www.smh.com.au/business/media-and-marketing/three-strikes-antipiracy-scheme-launched-in-wake-of-dallas-buyers-club-threat-20150410-1mgjyd.html

[870] Alan Randall, *Risk and precaution*: Cambridge University Press. (2011)

[871] Tom Randall, *While you were getting worked up over oil prices, this just happened to solar*, http://www.bloomberg.com/news/articles/2014-10-29/while-you-were-getting-worked-up-over-oil-prices-this-just-happened-to-solar, 2014

[872] C.N.R. Rao, A.K. Cheetham, Science and technology of nanomaterials: current status and future prospects. *Journal of Materials Chemistry*, 112887–2894, (2001)

[873] Jonathan Rauch, *The New Old Economy: oil, computers. and the reinvention of the earth*, http://www.theatlantic.com/past/docs/issues/2001/01/rauch.htm, 2001

[874] T. Ravichandran, Shu Han, Iftekhar Hasan, Effects of Institutional Pressures on Information Technology Investments: An Empirical Investigation. *IEEE Transactions on Engineering Management*, 56:4 677-691, (2009)

[875] Sarah Redshaw, *In the Company of Cars: Driving as a Social and Cultural Practices*; Lisa Dorn, Gerald Matthews, Ian Glendon, editors. Hampshire, England: Ashgate Publishing Ltd. (2008)

[876] Denise van Regemorter, *New energy externalities development for sustainability*. CES KULeuven, (2006) http://www.needs-project.org/RS1b/NEEDS_RS1b_TP8.1_8.2_8.3.pdf

[877] Robert F. Reilly, Robert P. Schweihs, *Valuing Intangible Assets*. New York: McGraw-Hill. (1998)

[878] I. Reinecke, Inside the Myer's Report - A nervous look confirms it's all unknowable. *The Australian Financial Review*, 14-15, (1980)

[879] Renewable Energy Advisors, *What is LCOE?*, http://www.renewable-energy-advisors.com/learn-more-2/levelized-cost-of-electricity/

[880] Nicholas Rescher, *Predicting the future: an introduction to the theory of forecasting*. Albany NY: State University of New York Press. (1997)

[881] Research Data Infrastructure Committee, *The Australian research data infrastructure strategy*. Canberra: Department of Industry, Innovation, Science, Research and Tertiary Education, (2014) http://docs.education.gov.au/system/files/doc/other/the_australian_research_data_infrastructure_strategy.pdf

[882] Kristy Revell, Stephen Allen Energy Use Behaviour Change. POSTNOTE: Houses of Parliament, (2012)

[883] Howard Rheingold, *Tools for thought: the history and future of mind-expanding technology* Cambridge MA: MIT Press. (2000)

[884] David Ribes, Thomas A Finholt, The long now of technology infrastructure: articulating tensions in development. *Journal of the Association for Information Systems*, 10:5 375-398, (2009)

[885] Ronald E Rice, Everett M Rogers, Reinvention in the Innovation Process. *Science Communication*, 1499-514, (1980)

[886] Neil M. Richards, William D. Smart How should the law think about robots? . Washington University in St Louis, (2013)

[887] Matt Ridley, *The rational optimist: how prosperity evolves*. New York: Harper Perennial. (2011)

[888] Ana Rincon, Michela Vecchi, Francisco Venturini, *ICT as a general purpose technology: spillovers, absorptive capacity and productivity performance*. National Institute of Economic and Social Research, (2013)

[889] Arie Rip, Controversies as informal technology assessment. *Knowledge: Creation, Diffusion, Utilization*, 8:2 349-371, (1986)

[890] Arie Rip, Thomas J Misa, Johan Schot, *Managing technology in society*. London: Pinter Publishers (1995)

[891] John B Robinson, Unlearning and backcasting: Rethinking some of the questions we ask about the future. *Technological Forecasting and Social Change*, 33:4 325-338, (1988)

[892] Katharine Rockett, Property Rights and Invention. *Handbook of the Economics of Innovation*: North-Holland (2010)

[893] Macario Rodriguez-Entrena, Melania Salazar-Ordonez, Influence of scientific-technical literacy on consumers' behavioural intentions regarding new food. *Apetite*, 60193-202, (2013)

[894] Everett M Rogers, *Diffusion of innovations*. New York: Simon and Schuster. (2010)

[895] Mark Rogers, *The definition and measurement of innovation*: Melbourne Institute of Applied Economic and Social Research Parkville, VIC. (1998)

[896] Jeffrey H Rohlfs, *Bandwagon effects in high technology industries*. Cambridge MA: MIT Press. (2003)

[897] Bernd Rohrmann, Risk perception of different societal groups: Australian findings and crossnational comparisons. *Australian Journal of Psychology*, 46:3 150-163, (1994)

[898] Bernd Rohrmann, Huichang Chen, Risk perception in China and Australia: An exploratory crosscultural study. *Journal of Risk Research*, 2:3 219-241, (1999)

[899] Denise Roland GSK to pump £200m into UK manufacturing. The Telegraph, (2013) http://www.telegraph.co.uk/finance/newsbysector/industry/10509063/GSK-to-pump-200m-into-UK-manufacturing.html

[900] Paul Romer, Idea gaps and object gaps in economic development. *Journal of Monetary Economics*, 32:3 543-573, (1993)

[901] Robert Root-Bernstein, I don't know! In: Bill Vitek, Wes Jackson, editors. *The virtues of ignorance: complexity, sustainability, and the limits of the land*. Lexington: University Press of Kentucky. pp. 233-250 (2008)

[902] Robert Root-Bernstein, The art of innovation: polymaths and universality of the creative process. In: Larisa V Shavinina, editor. *International Handbook on Innovation*. Oxford: Elsevier Science. pp. 267-278 (2003)

[903] Stephen Rosen, *Future facts: a forecast of the world as we will know it before the end of the century*. NY: Simon and Schuster. (1976)

[904] William Rosen, *The most powerful idea in the world: a story of steam, industry, and invention*. Chicago: University of Chicago Press. (2012)

[905] Nathan Rosenberg, Science, invention and economic growth. *The Economic Journal*, 84:333 90-108, (1974)

[906] Nathan Rosenberg, Technological interdependence in the American economy. *Technology and Culture*, 20:1 25-50, (1979)

[907] Nathan Rosenberg, *Inside the black box: technology and economics*. Cambridge: Cambridge University Press. (1982)

[908] Nathan Rosenberg, The impact of technological innovation: a historical view. In: Ralph Landau, Nathan Rosenberg, editors. *The positive sum strategy: harnessing technology for economic growth*. Washington DC: National Academy Press. pp. 17-32 (1986)

[909] Nathan Rosenberg, Economic experiments. *Industrial and Corporate Change*, 1:1 181-203, (1992)

[910] Nathan Rosenberg, Uncertainty and technological change. In: R Landau, T Taylor, G Wright, editors. *The mosaic of economic growth*. Stanford CA: Stanford University Press. pp. 91-125 (1996)

[911] Nathan Rosenberg, *Challenges to the social sciences in the new millennium*. Paris: OECD. 7-24 p, (2001)

[912] Nathan Rosenberg, Economic experiments. In: Giovanni Dosi, David A Teece, Josef Chytry, editors. *Understanding industrial and corporate change*. Oxford: Oxford University Press. pp. 287-308 (2005)

[913] Nathan Rosenberg, *Perspectives on technology*. Cambridge: Cambridge University Press. (2008)

[914] Nathan Rosenberg, *Schumpeter and the endogeneity of technology: some American perspectives*: Routledge. (2013)

[915] Nathan Rosenberg, LE Jr Birdzell, *How the West grew rich: the economic transformation of the industrial world*: Basic books. (2008)

[916] Joseph Rossman, *The psychology of the inventor: a study of the patentee*. Washington DC: Inventors Publishing Co. (1931)

[917] Peter L. Rousseau General purpose technologies. In: Durlauf Steven N., Blume Lawrene E., editors. The new Palgrave dictionary of economics. Second ed: Palgrave MacMillan, (2008)

[918] Royal Society, *The scientific century: security our future prosperity*. London: Royal Society, (2010)

[919] Royal Society, *Shut down or restart? The way forward for computing in UK schools*. London: Royal Society, (2012)

[920] A. Wendy Russell, Frank M. Vanclay, Janet G. Salisbury, Heather J. Aslin, Technology assessment in Australia: the case for a formal agency to improve advice to policy makers. *Policy Sci*, 44157-177, (2011)

[921] Andrew L Russell, *Open standards and the digital age: history, ideology, and networks*. New York: Cambridge University Press. (2014)

[922] Vernon W Ruttan, Usher and Schumpeter on invention, innovation, and technological change. *The Quarterly Journal of Economics*, 596-606, (1959)

[923] Vernon W Ruttan Sources of technical change: induced innovation, evolutionary theory and path dependence. EvolTheory Manuscript. Working Copy ed, (2001)

[924] Vernon W Ruttan, *General purpose technology, revolutionary technology, and technological maturity*. Dept. of Applied Economics, College of food, Agriculture and Natural Resource Sciences, University of Minnesota, (2008) http://cstpr.colorado.edu/students/envs_5100/nelson_1959.pdf

[925] Baram M. S, *An assessment of the use of CBA in regulatory decision making, retrospective technology assessment* Tarr J. A, editor: San Francisco Press Inc. (1976)

[926] Jathan Sadowski, Office of Technology Assessment: History, implementation, and participatory critique. *Technology in Society*, 429-20, (2015)

[927] Ilan Salomon, Technological change and social forecasting: the case of telecommuting as a travel substitute. *Transportation Research Part C: Emerging Technologies*, 6:1 17-45, (1998)

[928] Ammon J Salter, Ben R Martin, The economic benefits of publicly funded basic research: a critical review. *Research Policy*, 30:3 509-532, (2001)

[929] Paul A Samuelson, A note on measurement of utility. *The Review of Economic Studies*, 4:2 155-161, (1937)

[930] Dana Sanchez Bottling sunlight: using energy storage technology as a lens to view the factors affecting technological change in the electricty supply industry. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2014) http://acola.org.au/index.php/new-technologies-contributing-reports

[931] Dana Sanchez Collective technologies: autonomous vehicles. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2015) http://acola.org.au/index.php/new-technologies-contributing-reports

[932] Dana Sanchez Genetically modified crops: how attitudes to new technology influence adoption. Working paper of SAF05 project. Melbourne: Australian Council of Learned Academies, (2015) http://acola.org.au/index.php/new-technologies-contributing-reports

[933] Tiffany Sandell, Bernadette Sebar, Neil Harris, Framing risk: Communication messages in the Australian and Swedish print media surrounding the 2009 H1N1 pandemic. *Scandinavian Journal of Public Health*, 1403494813498158, (2013)

[934] Ozcan Saritas, M Atilla Oner, Systematic analysis of UK foresight results: joint application of integrated management model and roadmapping. *Technological Forecasting and Social Change*, 71:1 27-65, (2004)

[935] Henry Sauermann, Wesley M Cohen, *What makes them tick? Employee motives and firm innovation*. The National Bureau of Economic Research. 2134-2153 p, (2008)

[936] Eric R Scerri, *The periodic table: its story and its significance*: Oxford University Press. (2006)

[937] Daniel L. Schacter, Donna Rose Addis, Randy L. Buckner, Remembering the past to imagine the future: the prospective brain. *Nature reviews: Neuroscience*, 8657-661, (2007)

[938] Dietram A Scheufele, Communicating science in social settings. *Proceedings of the National Academy of Sciences*, 110:Supplement 3 14040-14047, (2013)

[939] Melissa A Schilling, Toward a general modular systems theory and its application to interfirm product modularity. *Academy of Management Review*, 25:2 312-334, (2000)

[940] Susanne K Schmidt, Raymund Werle, *Coordinating technology: studies in the international standardization of telecommunications*. Cambridge MA: MIT Press. (1998)

[941] Steven P Schnaars, *Megamistakes: forecasting and the myth of rapid technological change*. New York: Free Press. (1989)

[942] Steven P Schnaars, Swee L Chia, Cesar M Maloles III, Five modern lessons from a 55-year-old technological forecast. *Journal of Product Innovation Management*, 10:1 66-74, (1993)

[943] Donald A Schön, *Technology and change: The new Heraclitus*: Delta. (1967)

[944] Johan Schot, Frank W Geels, Niches in evolutionary theories of technical change. *Journal of Evolutionary Economics*, 17:5 605-622, (2007)

[945] Johan Schot, Arie Rip, The past and future of constructive technology assessment. *Technological forecasting and social change*, 54:2 251-268, (1997)

[946] Kathryn Schulz Being wrong: adventures in the margin of error. HarperCollins e-books, (c2010)

[947] Joseph Alois Schumpeter, *The theory of economic development: An inquiry into profits, capital, credit, interest, and the business cycle*: Transaction Publishers. (1934)

[948] Rachel Schurman, Fighting "Frankenfoods": Industry opportunity structures and the efficacy of the anti-biotech movement in Western Europe. *Social Problems*, 51:2 243-268, (2004)

[949] Peter Schwartz, *The art of the long view: planning for the future in an uncertain world*. New York: Doubleday. (1996)

[950] Richard E Sclove, *Reinventing technology assessment: a 21st century model*. Washington DC: Woodrow Wilson International Center for Scholars, (2010) http://wilsoncenter.org/techassessment

[951] Suzanne Scotchmer, *Innovation and incentives*. Cambridge: The MIT Press. (2004)

[952] James C Scott, *Seeing like a state: how certain schemes to improve the human condition have failed*. New Haven: Yale University Press. (1998)

[953] Marc C Scott, *How Much Will Australia's Dallas Buyers Club Pirates Have To Pay?*, http://www.gizmodo.com.au/2015/04/how-much-will-australias-dallas-buyers-club-pirates-have-to-pay/, 2015

[954] Peter B Scott-Morgan, *The reality of our global future: how five unstoppable high-tech trends will dominate our lives and transform our world*: Createspace. (2012)

[955] S Sebert, D Sharkey, H Budge, ME Symonds, The early programming of metabolic health: is epigenetic setting the missing link? *American Journal of Clinical Nutrition*, 94:6 suppl 1953S-1958S, (2011)

[956] Howard P. Segal, Assessing Retrospective Technology Assessment: A Review of the Literature. *Technology in Society*, 4231-246, (1982)

[957] Robert B Seidensticker, *Future hype: the myths of technology change*. San Francisco: Berrett-Koehler Publishers. (2006)

[958] Senate Select Committee, *Senate Select Committee on the National Broadband Network: Interim report*. Canberra, (2014)

[959] Senate Select Committee on the National Broadband Network Implications of the proposed National Broadband Network. In: The Senate, editor. 11 November 2008 ed. Canberra: Parliament of Australia, (2008)

[960] SGS Economics and Planning, *Cost benefit analysis - Key features and future directions*. (2012) http://www.sgsep.com.au/cost-benefit-analysis-key-features-and-future-directions

[961] Agam Shah, *Lapsing of Moore's Law opens up opportunity in chip design*, http://www.pcworld.com/article/2047552/lapsing-of-moores-law-opens-up-opportunity-in-chip-design.html, 2013

[962] Carl Shapiro, Hal R Varian, The art of standards wars. *California Management Review*, 41:2, (1999)

[963] Robert J Shapiro, *The US Software Industry As an Engine for Economic Growth and Employment*. Sonecon, (2014)

[964] Peter Sheehan, John Houghton, Bruce Rasmussen, Kim Sweeny, Greg Tegart, *Consistent national policies for converging technologies: some preliminary conclusions*. Melbourne: Centre for Strategic Economic Studies, Victoria University (2006)

[965] William A. Sherden, *The fortune sellers: the big business of buying and selling predictions*. New York: John Wiley. (1999)

[966] J. H. Shin, R.B. Haynes, Johnston. M.E., Effect of problem-based, self-directed undergraduate education on life-long learning. *Canadian Medical Association Journal*, 148:6 969-976, (1993)

[967] Donald C Shoup, *The high cost of free parking*. Berkeley CA: Transportation Center, (2011) http://www.uctc.net/papers/351.pdf

[968] Irving H Siegel, Technological change and long-run forecasting. *Journal of Business of the University of Chicago*, 26:3 141-156, (1953)

[969] G. Silberg, R. Wallace, *Self-driving cars: The next revolution*. KPMG and Center for Automotive Research. 36 p, (2012) http://www.kpmg.com/US/en/IssuesAndInsights/ArticlesPublications/Documents/self-driving-cars-next-revolution.pdf

[970] Richard S Silberglitt, Philip S. Antón, David R. Howell, Anny Wong, *The global technology revolution 2020, in-depth analyses: bio/nano/materials/information trends, drivers, barriers, and social implications*. Santa Monica CA: RAND Corporation. 083303975X 083303975X, (2006)

[971] Caroline Simard, Joel West, Knowledge networks and the geographic locus of innovation. In: Henry Chesbrough, Wim Vanhaverbeke, Joel West, editors. *Open innovation: researching a new paradigm*. Oxford: Oxford University Press. pp. 220-240 (2006)

[972] David Skellern Address to the annual meeting. Australian Academy of Technological Sciences and Engineering (ATSE) annual meeting. Homebush [Sydney]: Australian Academy of Technological Sciences and Engineering, (2010) https://http://www.atse.org.au/Documents/Publications/Orations/SPE 2010-11-13 David Skellern - AGM Oration Speech.doc

[973] Paul Slovic, Baruch Fischhoff, Sarah Lichtenstein, Facts versus fears: Understanding perceived risk. In: Daniel Kahneman, Paul Slovic, Amso Tversky, editors. *Judgment under uncertainty: Heuristics and biases*. Cambridge: Cambridge University Press. pp. 463-489 (1982)

[974] Jim Smith, Ravi Nair, *Virtual machines: versatile platforms for systems and processes*. Amsterdam: Elsevier. (2005)

[975] Joy Selby Smith, The report of the Committee of Inquiry into Technological Change in Australia : a review *Australian Quarterly*, 53:2 177-186, (1981)

[976] Merritt Roe Smith, Leo Marx, *Does technology drive history?: The dilemma of technological determinism*: MIT Press. (1994)

[977] M Smithson, *Ignorance and uncertainty: emerging paradigms*. New York: Springer-Verlag. (1989)

[978] Smithsonian Institution, *Carbons to Computers: Chairs*, January 2015, http://www.smithsonianeducation.org/educators/lesson_plans/carbons/chairs.html

[979] Luc Soete, Innovation, technology and productivity: why Europe lags behind the United States and why various European economies differ in innovation and productivity. In: Manuel Castells, Gustavo Cardoso, editors. *The network society: from knowledge to policy*: Center for Transatlantic Relations, Johns Hopkins University. pp. 125-148 (2005)

[980] Ricard V Solé, Sergi Valverde, Marti Rosas Casals, Stuart A Kauffman, Doyne Farmer, et al., The evolutionary ecology of technological innovations. *Complexity*, 18:4 15-27, (2013)

[981] Paul Sollie, Marcus Düwell, editors *Evaluating New Technologies: Methodological Problems for the Ethical Assessment of Technology Developments*: Springer. (2009)

[982] Robert Solow We'd better watch out (review of Manufacturing Matters: The Myth of the Post-Industrial Economy). New York Times Book Review, (1987)

[983] Jeff Sommerfeld, Laurie Buys, Australian consumer attitudes and decision making on renewable energy technology and its impact on the transformation of the energy sector. *Open Journal of Energy Efficiency*, 3:3 85-91, (2014)

[984] Qing Song, Shaosan S Wang, A Maziar Zafari, Genetics of the metabolic syndrome. *Hospital Physician*:October 51-61, (2006)

[985] Ashish Sood, Gareth M James, Gerard J Tellis, Ji Zhu, Predicting the path of technological innovation: SAW vs. Moore, bass, gompertz, and kryder. *Marketing Science*, 31:6 964-979, (2012)

[986] Ashish Sood, Gerard J Tellis, Technological evolution and radical innovation. *Journal of Marketing*, 152-168, (2005)

[987] Corinna Sorenson, Michael Drummond, Panos Kanavos, *Ensuring value for money in health care: the role of health technology assessment in the European Union*. Bodmin, Cornwall: European Observatory on Health Systems and Policies. (2008)

[988] Benjamin K. Sovacool, The costs of failure: A preliminary assessment of major energy accidents, 1907–2007. *Energy Policy*, 361802-1820, (2008)

[989] Brennan Spies, Web services, part 1: SOAP vs. REST, 2 May 2008, http://www.ajaxonomy.com/2008/xml/web-services-part-1-soap-vs-rest

[990] UK Department for Culture Media & Sport, *Creative industries mapping document*. Gov.uk, (2001) https://http://www.gov.uk/government/publications/creative-industries-mapping-documents-2001

[991] Vineet Srivastava, Mehul Motani Cross-layer Design: A Survey and the Road Ahead. IEEE Communications Magazine. pp. 112-119, (2005)

[992] Brian Stableford, David Langford, *The third millennium: a history of the world AD 2000-3000*. New York: Alfred A Knopf. (1985)

[993] Standards.gov, *What are Standards?*, April 2015, http://standards.gov/standards_gov/Standards.cfm

[994] Stanford2025, *Learning and Living at Stanford*, http://www.stanford2025.com

[995] Autumn Stanley, *Mothers and daughters of invention: Notes for a revised history of technology*. USA: Rutgers University Press. (1995)

[996] Mark Staples, Critical rationalism and engineering: methodology. *Synthese*, 192:1 337-362, (2015)

[997] Susan Leigh Star, The ethnography of infrastructure. *American Behavioral Scientist*, 43:3 377-391, (1999)

[998] Statistics New Zealand, *Innovation in New Zealand: 2011*. Wellington: Statistics New Zealand, (2011) http://www.stats.govt.nz/browse_for_stats/businesses/business_growth_and_innovation/innovation-in-new-zealand-2011.aspx

[999] Martine Stead, Ross Gordon, Ingrid Holme, Crawford Moodie, Gerard Hastings, et al., *Changing attitudes, knowledge and behaviour. A review of successful initiatives.*: Joseph Rowntree Foundation, (2009)

[1000] Scott Steel, The CSIRO gets HIP to debunking media hysteria, 14 April 2011, http://blogs.crikey.com.au/pollytics/2011/04/24/the-csiro-gets-hip-to-debunking-media-hysteria/

[1001] H Kevin Steensma, Louis Marino, K Mark Weaver, Attitudes toward cooperative strategies: A cross-cultural analysis of entrepreneurs. *Journal of International Business Studies*, 591-609, (2000)

[1002] Linda Steg, Car use: lust and must. Instrumental, symbolic and affective motives for car use. *Transportation Research Part A: Policy and Practice*, 39:2 147-162, (2005)

[1003] Daniela Stehlik, *Understanding the formation of attitudes to nuclear power in Australia*. National Academies, (2010) http://www.naf.org.au/index.htm

[1004] Dennis Steiger, NBN Co: at the cutting edge of global broadband, 13 March 2015,

[1005] Paula E. Stephan, The Economics of Science. In: Paul Stoneman, editor. *Handbook of the economics of innovation and technological change*: Blackwell Oxford (1995)

[1006] Kim Sterelny, Made by each other: organisms and their environment. *Biology and Philosophy*, 2021-36, (2005)

[1007] Luke A Stewart, The Impact of Regulation on Innovation in the United States: A Cross-Industry Literature Review. *Institute of Medicine*, (2010)

[1008] Gerry Stoker, Exploring the promise of experimentation in political science: micro-foundational insights and policy relevance. *Political Studies*, 58300-319, (2010)

[1009] Gerry Stoker, Translating experiments into policy. *Annals of the American Academy*, 62847-58, (2010)

[1010] Donald E Stokes, *Pasteur's quadrant: Basic science and technological innovation*: Brookings Inst Press. (1997)

[1011] Alexandra Stone, Susan Rose, Bhavya Lal, Stephanie Shipp, *Measuring innovation and intangibles: a business perspective*. Washington DC: Institute for Defense Analyses, Science & Technology Policy Institute, (2008)

[1012] Marshall Stoneham, The quantum in your materials world. *Materials Today*, 11:9 32-36, (2008)

[1013] David Stradling, Peter Thorsheim, The smoke of great cities: British and American efforts to control air pollution, 1860-1914. *Environmental History*, 46-31, (1999)

[1014] Ramesh Subramanian, Brian D Goodman, *Peer-to-peer computing: The Evolution of a Disruptive Technology*: Igi Global. (2005)

[1015] I Putu Sudiana How effective is cost-benefit analysis in assisting decision making by public sector managers? Case studies of two Australian departments. Crawford School of Economics and Government, The Australian National University, (2010)

[1016] Elizabeth Suhay, James N. Druckman, The Politics of Science: Political Values and the Production, Communication, and Reception of Scientific Knowledge. *The ANNALS of the American Academy of Political and Social Science*, 658:1 6-15, (2015)

[1017] Cass R. Sunstein, Empirically Informed Regulation. *The University of Chicago Law Review*, 781349-1429, (2011)

[1018] Sunstien C, *Simpler: The Future of Government*. New York: Simon & Schuster. (2013)

[1019] MA Suter, PM Vuquin, K Hartil, A Fiallo, RA Harris, et al., In utero exposure to a maternal high-fat diet alters the epigenetic histone code in a murine model. *American Journal of Obstetrics and Gynecology*, 210:5 463.e461-463.e411, (2014)

[1020] Peter Swann, Jas Gill, *Corporate vision and rapid technological change: the evolution of market structure*. London: Routledge. (2002)

[1021] SS Swords, *Technical history of the beginnings of radar*; B Bowers, C Hempstead, editors. London: Institution of Engineering and Technology. (2008)

[1022] Karl K. Szpunar, Jason M. Watson, Kathleen B. McDermott, Neural substrates of envisioning the future. *PNAS*, 104:2 642–647, (2007)

[1023] Jim Tankersley, *A black hole for our best and brightest*, http://www.washingtonpost.com/sf/business/2014/12/16/a-black-hole-for-our-best-and-brightest/, 2014

[1024] Joel A. Tarr, editor *Retrospective Technology Assessment - 1976*. California: San Francisco Press. (1977)

[1025] Joel A. Tarr, James McCurley III, Francis C. McMichael, Terry Yosie, Water and Wastes: A Retrospective Assessment of Wastewater Technology in the United States, 1800-1932. *Technology and Culture*, 25226-263, (1984)

[1026] Gregory Tassey, Standardization in technology-based markets. *Research Policy*, 29:4-5 587-602, (2000)

[1027] Gregory Tassey, *The technology imperative*. UK: Edward Elgar Publishing. (2007)

[1028] Edward M Tauber, How market research discourages major innovation. *Business Horizons*, 17:3 22-26, (1974)

[1029] Joshua Tauberer, *Open government data: the book*: Joshua Tauberer. (2014)

[1030] FW Taussig, *Inventors and money-makers: lectures on some relations between economics and psychology delivered at Brown University*. NY: Macmillan Company. (1915)

[1031] Carol Tavris, Elliot Aronson Mistakes were made (but not by me): why we justify foolish beliefs, bad decisions, and hurtful acts. (c2013) http://ebookforexperts.blogspot.com.au/2013/05/mistakes-were-made-but-not-by-me-why-we_8517.html

[1032] David J Teece, Profiting from technological innovation: implications for integration, collaboration, licensing and public policy. *Research Policy*, 15:6 285-305, (1986)

[1033] Edward Tenner, *Why things bite back: technology and the revenge of unintended consequences*. New York: Vintage Books. (1997)

[1034] Philip E Tetlock, *Expert political judgment*. Princeton: Princeton University Press. (2005)

[1035] The Dorking Desk Shop & Elias Antiques of Dorking, *A potted history of writing furniture*, January 2015, http://desk.uk.com/history/

[1036] The Economist, *Les misérables*, http://www.economist.com/node/21559618, 2012

[1037] The Expert Panel on the State of Canada's Science Culture, *Science Culture: Where Canada Stands*. Ottawa: The Council of Canadian Academies, (2014)

[1038] The US National Academies, *Hidden Costs of Energy: Unpriced consequences of energy production and use*. Washington: The National Academies, (2010)

[1039] B Thidé, F Tamburini, H Then, CG Someda, RA Ravanelli The physics of angular momentum radio. pp. arXiv:1410.4268v1411, (2014)

[1040] Adam Thierer, What is 'optimal interoperability'? A review of Palfrey & Gasser's 'Interop', 11 June 2012, http://techliberation.com/2012/06/11/what-is-%E2%80%9Coptimal-interoperability%E2%80%9D-a-review-of-palfrey-gasser%E2%80%99s-%E2%80%9Cinterop%E2%80%9D/

[1041] Dave Thomas, Agile is dead (long live agility), 4 March 2014, http://pragdave.me/blog/2014/03/04/time-to-kill-agile/

[1042] Hedley Thomas, *Queensland floods class action to begin in NSW Supreme Court* http://www.theaustralian.com.au/news/nation/queensland-floods-class-action-to-begin-in-nsw-supreme-court/story-e6frg6nf-1226981310824, 2014

[1043] Peter Thompson, Learning by doing. In: Bronwyn H Hall, Nathan Rosenberg, editors. *Economics of Innovation*. Amsterdam: Elsevier (2010)

[1044] Stephen Thompson, *1871 The Overland Telegraph Line: Telegraph Collection*, http://www.migrationheritage.nsw.gov.au/exhibition/objectsthroughtime/1871-the-overland-telegraph-line-telegraph-collection/,

[1045] LJ Thorburn, J Langdale, Embracing Change-Case Studies on How Australian Firms Use Incremental Innovation to Support Growth. *Canberra: Department of Industry, Tourism and Resources*, (2003)

[1046] Gunther Tichy, The over-optimism among experts in assessment and foresight. *Technological Forecasting and Social Change*, 71:4 341-363, (2004)

[1047] Time Customs: give me liberty. Time, (1962) http://content.time.com/time/magazine/article/0,9171,827416,00.html

[1048] Peter Tingling, Michael Parent, An exploration of enterprise technology selection and evaluation. *Journal of Strategic Information Systems*, 13329-354, (2004)

[1049] Andrew Torrance, Bill Tomlinson, Patents and the regress of useful arts. *Columbia Science and Technology Law Review*, 10, (2009) http://www.stlr.org/cite.cgi?volume=10&article=3

[1050] Phil Torres, *Human evolution and technology: from Prosimian to posthuman*, http://ieet.org/index.php/IEET/more/verdoux20100416, 2010

[1051] Tourism New Zealand, *Great Kiwi Inventions*, 13 Februray 2015, http://media.newzealand.com/en/story-ideas/great-kiwi-inventions/

[1052] Charles H Townes, Quantum electronics, and surprise in development of technology: the problem of research planning. *Science*, 159:3816 699-703, (1968)

[1053] Paul Joseph Tranter, Speed kills: the complex links between transport, lack of time and urban health. *Journal of Urban Health*, 87:2 155-166, (2010)

[1054] Pat Treacy, Sophie Lawrance, FRANDly fire: are industry standards doing more harm than good? *Journal of Intellectual Property Law & Practice*, 3:1 22-29, (2008)

[1055] Treasury, *Strong growth low pollution: modelling a carbon price* Canberra: Commonwealth of Australia, (2011) http://carbonpricemodelling.treasury.gov.au/content/report.asp

[1056] Mary Tripsas, Technology, identity, and inertia through the lens of "The Digital Photography Company". *Organization Science*, 20:2 441-460, (2009)

[1057] Robert Trivers, *The folly of fools: the logic of deceit and self-deception in human life*. New York: Basic Books. (2011)

[1058] Yaacov Trope, Nira Liberman, Temporal construal. *Psychological Review*, 110:3 403-421, (2003)

[1059] Grétar Tryggvason, Diran Apelian, editors *Shaping our world: engineering education for the 21st century*. Hoboken NJ: John Wiley & Sons. (2012)

[1060] Nicos L Tsilas, Open innovation and interoperability. In: Laura DeNardis, editor. *Opening standards: the global politics of interoperability*. Cambridge MA: MIT Press. pp. 97-117 (2011)

[1061] Sherry Turkle, *The second self: Computers and the human spirit*: MIT Press. (2005)

[1062] Sherry Turkle, *Alone together: why we expect more from technology and less from each other*. USA: Basic Books. (2011)

[1063] Malcolm Turnbull, *Transitioning NICTA to a self-sustainable model*, http://www.minister.communications.gov.au/malcolm_turnbull/news/transitioning_nicta_to_a_self-sustainable_model - .VThDT5PD9bY

[1064] Malcolm Turnbull The power of open data. Locate 15 Conference. Brisbane, (2015)

[1065] Bruno Turnheim, Frank W Geels, The destabilisation of existing regimes: Confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967). *Research Policy*, 421749-1767, (2013)

[1066] Michael L Tushman, Lori Rosenkopf, Organizational determinants of technological-change-toward a sociology of technological evolution. *Research in Organizational Behavior*, 14311-347, (1992)

[1067] Amos Tversky, Daniel Kahneman, Evidential impact of base rates. In: Daniel Kahneman, Paul Slovic, Amos Tversky, editors. *Judgment under uncertainty: heuristics and biases*: Cambridge University Press. pp. 153-163 (1982)

[1068] UK Cabinet Office, *Risk: improving government's capability to handle risk and uncertainty*. London: Cabinet Office, (2002)

[1069] UK Government, *Innovate UK Technology Strategy Board*, https://http://www.gov.uk/government/organisations/innovate-uk

[1070] UK Government Office for Science, *Chief Scientific Advisers*, 15 April 2015, https://http://www.gov.uk/government/organisations/government-office-for-science/groups/chief-scientific-advisers

[1071] David S. Unger, MythBusters and the joy of technology. *Technology and Culture*, 55:2 484, (2014)

[1072] United Nations, *Comprehensive Study on Cybercrime*. Vienna: UNODC, (2013) http://www.unodc.org/documents/commissions/CCPCJ_session22/13-80699_Ebook_2013_study_CRP5.pdf

[1073] United States Government Accountability Office Traffic Congestion: Road Pricing Can Help Reduce Congestion, but Equity Concerns May Grow. Report to the Subcommittee on Transportation, Housing, and Urban Development and Related Agencies, Committee on Appropriations, House of Representatives, (2012)

[1074] University of Cambridge, *Chapter XIII: Finance and Property*, April 2015, http://www.admin.cam.ac.uk/univ/so/pdfs/ordinance13.pdf

[1075] Rice University, *Machine Learning for Education - ICML2015 workshop*, 14 July 2015, http://dsp.rice.edu/ML4Ed_ICML2015

[1076] Gregory C Unruh, Understanding carbon lock-in. *Energy Policy*, 28:12 817-830, (2000)

[1077] Gregory C Unruh, Escaping carbon lock-in. *Energy Policy*, 30:4 317-325, (2002)

[1078] US Congress, *Technology and the American economic transition: choices for the future*. Washington DC: US Congress, Office of Technology Assessment, (1988)

[1079] US Congress Office of Technology Assessment, *Technology and structural unemployment: reemploying displaced adults*. Washington DC: United States Government Printing Office, (1986)

[1080] US Congress Office of Technology Assessment, *Finding a Balance: Computer Software, Intellectual Property and the Challenge of Technological Change*. Washington: U.S. Government Printing Office, (1992)

[1081] US Government Chief Information Officer, *Digital government: building a 21st century platform to better serve the American people*. (2012) https://http://www.whitehouse.gov/sites/default/files/omb/egov/digital-government/digital-government-strategy.pdf

[1082] US Office of the Director of National Intelligence, *The 2011 National Counterterrorism Center report on terrorism*. Washington DC: Office of the Director of National Intelligence (2012) https://web.archive.org/web/20121006185422/http://www.nctc.gov/docs/2011_NCTC_Annual_Report_Final.pdf

[1083] Abbot Payson Usher, *A History Mechanical Inventions*: Harvard University Press. (1954)

[1084] Walter D Valdivia, *University start-ups: critical for improving technology transfer*. Washington DC: Center for Technology Innovation, Brookings Institution, (2013)

[1085] Ibo van de Poel, On the role of outsiders in technical development. *Technology Analysis & Strategic Management*, 12:3 383-397, (2010)

[1086] Andrew H Van de Ven, Raghu Garud, Innovation and industry development: the case of cochlear implants. *Research on Technological Innovation, Management and Policy*, 51-46, (1993)

[1087] Jeroen C.J.M.; Georgios K van den Bergh, Evolutionary Policy. *Papers on economics and evolution*, (2009)

[1088] Rinie van Est, Frans Brom, Technology assessment as an analytic and democratic practice. In: Ruth Chadwick, editor. *Encyclopedia of Applied Ethics*. 2nd ed. London: Elsevier (2012)

[1089] Harro van Lente, Arie Rip, Expectations in technological developments: an example of prospective structures to be filled by agency. In: Cornelis Disco, Barend van der Meulen, editors. *Getting new technologies together: studies in making sociotechnical order*. no 82 ed. Berlin: Walter de Gruyter (1998)

[1090] Patricia van Vliet, Mirjam Knape, Jeroen de Hartog, Nicole Janssen, Hendrik Harssema, et al., Motor vehicle exhaust and chronic respiratory symptoms in children living near freeways. *Environmental research*, 74:2 122-132, (1997)

[1091] Hal R Varian Innovation, components and complements. University of California, Berkeley, (2003)

[1092] Tyler J Veak, *Democratizing technology: Andrew Feenberg's critical theory of technology*: Suny Press. (2012)

[1093] Thorstein Veblen, *The Instinct of Workmanship: And the state of the industrial arts*. New York: MacMillan Company. (1914)

[1094] Ian de Vere Developing creative engineers: a design approach to engineering education. International Conference on Engineering and Product Design Education. University of Brighton (UK), (2009)

[1095] Roberto Verganti, *Design driven innovation: changing the rules of competition by radically innovating what things mean*: Harvard Business School Press. (2009)

[1096] Charles M Vest, Educating engineers for 2020 and beyond 9 January 2007, http://engineeringchallenges.org/cms/7126/7639.aspx

[1097] Edward Vine, Michael Sullivan, Loren Lutzenhiser, Carl Blumstein, Bill Miller, Experimentation and the evaluation of energy efficiency programs. *Energy Efficiency*, 7627-640, (2014)

[1098] Vernon Vinge The coming technological singularity: how to survive in the post-human era. VISION-21 Symposium, (1993) https://www-rohan.sdsu.edu/faculty/vinge/misc/singularity.html

[1099] Vivianne HM Visschers, Michael Siegrist, How a nuclear power plant accident influences acceptance of nuclear power: Results of a longitudinal study before and after the Fukushima disaster. *Risk analysis*, 33:2 333-347, (2013)

[1100] Patrick Vlaskovits, Henry Ford, innovation, and that "faster horse" quote, 29 August 2011, https://hbr.org/2011/08/henry-ford-never-said-the-fast/

[1101] Andreas von Bubnoff, The 1918 flu virus is resurrected. *Nature*, 437:7060 794-795, (2005) http://www.nature.com/nature/journal/v437/n7060/full/437794a.html

[1102] Eric Von Hippel, *The sources of innovation*. New York: Oxford University Press. (1988)

[1103] Eric Von Hippel, Democratizing innovation: the evolving phenomenon of user innovation. *Journal für Betriebswirtschaft*, 55:1 63-78, (2005)

[1104] Eric Von Hippel, *Democratizing innovation: the evolving phenomenon of user innovation*. Cambridge MA: MIT Press. (2005)

[1105] Eric Von Hippel, Ralph Katz, Shifting innovation to users via toolkits. *Management Science*, 48:7 821-833, (2002)

[1106] Eric Von Hippel, Susumo Ogawa, Jeroen PG de Jong, The age of consumer-innovator. *MIT Sloan Management Review*, 53:1 27-35, (2011)

[1107] Gerhard Vorster, Chris Richardson, David Redhill, *Get out of your own way: unleashing productivity*. Sydney: Deloitte Touche Tohmatsu, (2014)

[1108] CA Voss, Multiple independent invention and the process of technological innovation. *Technovation*, 2169-184, (1984)

[1109] Judy Wajcman, *Feminism Confronts Technology*. USA: Pennsylvania State University Press. (1991)

[1110] Gordon G Wallace, Rhys Cornock, Cathal D O'Connell, Stephen Beirne, Susan Dodds, et al. 3D bioprinting: printing parts for bodies. ARC Centre of Excellence for Electromaterials Science, (2014)

[1111] Peter Walton, Tegan Kop, David Spriggs, Brendan Fitzgerald, A digital inclusion: Empowering all Australians. *Australian Journal of Telecommunications and the Digital Economy*, 1:1, (2013)

[1112] Brian Wang Deaths per TWH by energy source. Next Big Future, (2011) nextbigfuture.com

[1113] J Wang, Z Wu, D Li, SV Dindot, MC Satterfield, et al., Nutrition, epigenetics, and metabolic syndrome. *Antioxid Redox Signal*, 17:2 282-301, (2012)

[1114] Washington's Blog, The terrorism statistics every American needs to hear, 21 February 2015, http://www.globalresearch.ca/the-terrorism-statistics-every-american-needs-to-hear/5382818 - sthash.uOitdVSm.dpuf

[1115] Amy D Waterman, Jane Garbutt, Erik Hazel, William Claiborne Dunagan, Wendy Levinson, et al., The emotional impact of medical errors on practicing physicians in the United States and Canada. *Joint Commission Journal on Quality and Patient Safety*, 33:8 467-476, (2007)

[1116] John Elfreth Watkins, Jr, What may happen in the next hundred years. *Ladies Home Journal*, (1900)

[1117] Karl E Weick, Kathleen Sutcliffe, M, *Managing the unexpected: resilient performance in an age of uncertainty*. San Francisco: John Wiley & Sons. (2007)

[1118] Bruce A. Weinberg, *Experience and Technology Adoption*. Institute for the Study of Labor, (2004) http://hdl.handle.net/10419/20286

[1119] Martin L Weitzman, Recombinant growth. *The Quarterly Journal of Economics*, 113:2 331-360, (1998)

[1120] Jameson M Wetmore, Amish technology: Reinforcing values and building community. *Technology and Society Magazine, IEEE*, 26:2 10-21, (2007)

[1121] Leesa Wheelahan, John Buchanan, Serena Yu, *Linking qualifications and the labour market through capabilities and vocational streams*. Adelaide: National Centre for Vocational Education Research. (2015)

[1122] John Archibald Wheeler, A septet of Sibyls: aids in the search for truth. *American Scientist*, 44:4 360-377, (1956)

[1123] James Q Whitman, The two western cultures of privacy: Dignity versus liberty. *Yale Law Journal*, 1151-1221, (2004)

[1124] Martin J Wiener, *English culture and the decline of the industrial spirit, 1850-1980*. Cambridge: Cambridge University Press. (2004)

[1125] Wikipedia, *DOCSIS*, http://en.wikipedia.org/wiki/DOCSIS

[1126] Wikipedia, *History of radar*, April 2015, http://en.wikipedia.org/wiki/History_of_radar

[1127] Wikipedia, *Singularity*, April 2015, http://en.wikipedia.org/wiki/Singularity

[1128] Wikipedia, *World GDP (1990 international dollars)*, 28 May 2015, http://en.wikipedia.org/wiki/World_economy

[1129] Wikipedia, *Banqiao Dam*, February 2015, http://en.wikipedia.org/wiki/Banqiao_Dam

[1130] Wikipedia, *2010–11 Queensland floods*, http://en.wikipedia.org/wiki/2010%E2%80%9311_Queensland_floods - Inquiry

[1131] Wikipedia, *Externalities*, http://en.wikipedia.org/wiki/Externality

[1132] Wikipedia, *Option Value (cost-benefit analysis)*, http://en.wikipedia.org/wiki/Option_value_(cost_benefit_analysis)

[1133] Rosalind Williams, Our technological age, from the inside out. *Technology and Culture*, 55:2 461-476, (2014)

[1134] Robert C Williamson NICTA submission to boosting the commercial returns of research. (2014) https://submissions.education.gov.au/Forms/higher-education-research/pages/item?SubmissionID=BCR1400024

[1135] John S Wilson, Standards, trade, and development. In: Laura de Nardis, editor. *Opening standards: the global politics of interoperability*. Cambridge MA: MIT Press. pp. 119-131 (2011)

[1136] Langdon Winner, *Autonomous technology: Technics-out-of-control as a theme in political thought*. Cambridge: The MIT Press. (1978)

[1137] Langdon Winner, Technology today: utopia or dystopia? *Social Research*, 64:3 989-1017, (1997)

[1138] George Wise, The accuracy of technological forecasts, 1890–1940. *Futures*, 8:5 411-419, (1976)

[1139] George Wise, Technological prediction, 1890-1940 [PhD Thesis]: Boston University, (1976)

[1140] Karl A. Wittfogel Developmental Aspects of Hydraulic Societies. Irrigation Civilizations: A Comparative Study: Department of Cultural Affairs, Pan Amaerican Union. pp. 43-57, (1955)

[1141] David Wogan, What the world of 2014 looks like, according to Isaac Asimov in 1964, 1 January 2014, http://blogs.scientificamerican.com/plugged-in/2014/01/01/what-the-world-of-2014-looks-like-according-to-isaac-asimov-in-1964/

[1142] T. Wohlers, *Wohlers Report 2012: Additive Manufacturing and 3D Printing State of the Industry*. Colorado, Fort Collins. 125, 131 p, (2012)

[1143] Tom Wolfe, *The right stuff*. New York: Farrar, Straus and Giroux. (1979)

[1144] Anny Wong The Global Technology Revolution 2020: Trends, Drivers, Barriers, and Social Implications. Washington DC: AAAS Forum on Science and Technology Policy: Session on "Building Science, Technology, and Innovation Capacity in Developing Countries", (2007)

[1145] Diana F. Wood, Problem based learning. *BMJ*, 326:7384 328-330, (2003)

[1146] Tony Wood, Tristan Edis, Daniel Mullerworth, Helen Morrow, *No easy choices: which way to Australia's energy future? Technology analysis*. Melbourne: Grattan Institute, (2012)

[1147] World Health Organization, *Tobacco*, 30 May 2015, http://www.who.int/mediacentre/factsheets/fs339/en/

[1148] Fred Woudenberg, An evaluation of Delphi. *Technological Forecasting and Social Change*, 40:2 131-150, (1991)

[1149] Richard Wrangham, *Catching fire: how cooking made us human*. New York: Basic Books. (2009)

[1150] Richard W Wrangham, James Holland Jones, Greg Laden, David Pilbeam, Nancy Lou Conklin-Brittain, The raw and the stolen: cooking and the ecology of human origins. *Current Anthropology*, 40:5 567–594, (1999) http://web.stanford.edu/~jhj1/papers/wrangham_etal1999.pdf

[1151] George Wright, George Cairns, *Scenario thinking: practical approaches to the future*: Palgrave Macmillan. (2011)

[1152] Theodore Wright, Factors affecting the costs of airplanes. *Journal of the Aeronautical Sciences*, 3122-128, (1936)

[1153] Albert W Wu, Medical error: the second victim. *BMJ*, 320726-727, (2000)

[1154] Yan Yan, Guodong Xie, Martin PJ Lavery, Hao Huang, Nisar Ahmed, et al., *High-capacity millimetre-wave communications with orbital angular momentum multiplexing*, 2014

[1155] Y.Y. Yusuf, M. Sarhadi, A. Gunasekaran, Agile manufacturing: the drivers, concepts and attributes. *International Journal of Production Economics*, 6233-43, (1999)

[1156] Micah Zenko, America is a safe place, 24 February 2012, http://blogs.cfr.org/zenko/2012/02/24/america-is-a-safe-place/

[1157] Chunfang Zhou, Fostering creative engineers: a key to face the complexity of engineering practice. *European Journal of Engineering Education*, 37:4 343-353, (2012)

[1158] John Ziman, *Technological innovation as an evolutionary process*. Cambridge: Cambridge University Press. (2003)

[1159] Jonathan Zittrain, *The future of the internet - and how to stop it*. New Haven CT: Yale University Press. (2008)

[1160] Glenn Zorpette, *Waiting for the rapture: technological convergence will change our lives but won't make them indefinitely long*, http://spectrum.ieee.org/biomedical/ethics/waiting-for-the-rapture, 2008

Appendix 1: Understanding impacts

Some impacts of technology, or lenses through which to understand its impacts

	Effect	Explanation	Examples
1.	Tragedy of the commons	Depletion of a common resource, against a group's long-term best interests, through the action of individual members in a complex system behaving independently and rationally according to short-term self-interest. This common resource can be concrete (water, fish, timber, or minerals, for example), or intangible (social capital, knowledge commons, privacy, cultural heritage). Lock-in and inertia Hierarchy of needs Standards	Peak data [228]: As demand for data and consumption of data rapidly increase, Australia's wireless communications landscape faces the possibility of a 'spectrum crunch', when user demand will outstrip the capacity of the radiofrequency spectrum. 'With more and more essential services, including medical, education and government services, being delivered digitally and on mobile devices, finding a solution to 'peak data' will become ever more important into the future' [306]. Automobiles: every driver in a road system imposes a small congestion cost to other drivers, cyclists and pedestrians. Cars also produce harmful pollutants, including ozone and carbon dioxide. Surface parking and roads themselves use up valuable urban real estate, and free parking 'encourages too many people to drive, and it encourages people to stay in free spots longer than the welfare-maximising amount of time'. Drivers circle, looking for empty car parks, fuelling the congestion problem. Furthermore, each car on a road imposes a maintenance cost. As each driver considers the cost he or she imposes to be small compared to the convenience of driving and free parking, roads are overused, leading to traffic congestion, air pollution, poorly maintained and costly road infrastructure, and opportunity costs [57,967] (Appendix Locked into the car,[765]). Waste disposal: While the waste products of human action are a prime example of the tragedy of the commons, technology can also help mitigate the tragedy of the commons. More efficient, effective, and affordable methods of manufacture can help to produce less waste, while recycling technologies can reuse by-products of technology. The choice of a standard can lead to lock in – choice of width of train tracks, or 110V or 220V makes it difficult to change later when infrastructure is in place. What seems deterministic to later generations is actually as a result of a decision by society e.g. Dutch housing accommodates bikes versus sprawl in US and Australia that accommodates cars [776].

2.	Vested interest	Lock-in Early adoption leading to market dominance	'Industrial economies have been locked into fossil fuel-based energy systems through a process of technological and institutional co-evolution driven by path-dependent increasing returns to scale' – Unruh's 'techno-institutional complex' [1076]. This effect can lead to agents whose financial interests are best supported by maintaining the status quo. The QWERTY keyboard was designed to slow down typists so that adjoining keys on a typewriter would not jam. The Dvorak keyboard was a more efficient arrangement based on the letters most often used, and designed so that successive strokes fell on alternate hands to minimise risk of repetition strain injury risks. The change has obvious advantages but was not adopted; vested interest by manufacturers and typists themselves, considerable effort to change design and to learn [894].
3.	Competitive advantage	Early adoption Lock-in Network effects Efficiency of production Efficient business processes Flexibility Distance from market Better marketing Better product	Refer to Appendix Bottling sunlight: energy storage technologies,[930] Refer to Appendix Locked into the car[765] In 1954, in light of the development of solid-state devices like the transistor in the United States, which replaced cumbersome, unreliable vacuum tubes, leading to much faster, smaller computers, CSIRO terminated its CSIRAC mainframe computer program. Export restrictions and cost caused by Australia's physical isolation from the largest markets gave other nations a significant competitive advantage and meant that the growth of a globally significant hardware industry in Australia was unlikely, see[305]. 3D printing is a good example of creating competitive advantage, see Appendix Printing the future? An analysis of the hype and hope of rapid prototyping technology[541]
4.	Wealth and resource distribution	Hierarchy of need Early adoption Market share Stable political and regulatory landscape	As technologies for health, nutrition, education, information, communication etc. are progressively adopted in a region, availability of wealth and resources may become more widespread within that region. The citizens of a country with the ability to exploit its natural, technological, social, and intellectual resources for their own benefit will be strongly motivated. IBM's existing market share in the 1940s allowed the company to capitalise on early developments in digital programmable computing and secure a large share of the business computing market during the 1950s and 1960s. Although the company then entered the personal computer scene late (during the 1980s), this early market share allowed the company to remain a key supplier and developer of business computing into the 21st century see [305]
5.	Inequality and its symptoms, for instance, in the	Physical, economic and skills barriers to the uptake of technologies	Differences in skills and education, which may be motivated by social and economic factors, are key elements in maintaining the digital divide.

	form of a digital (or other kind of technological) divide	or processes may perpetuate inequality Economic barriers that limit resources and prevent people from obtaining or otherwise using newer technologies Lack of skill, knowledge, or receptiveness	Regional differences may play a role too. For example, access to broadband technology is greater in urban areas than rural and regional areas of Australia. This can perpetuate problems of isolation and uneven opportunity, as well as uptake and adoption. Country people rely more on wireless communication than people in cities who can easily travel to an appointment. For example, broadband courses will help country people more than city people. A digital divide may perpetuate socio-economic inequalities in a number of different ways. • People who are not digitally literate, which may include some elderly people, some new migrants, and others who for various reasons lack digital skills and education, will be unable to negotiate and capitalise on increasingly digitally-connected civic domains. As a result, they may have poorer access to government services, poorer job prospects, and suffer social exclusion. • People from lower socio-economic status backgrounds may be less likely to have access to digital technologies for social, economic and geographical reasons. Even when access is available, they may not have the capacity to exploit digital resources, as a result of lack of awareness, training and knowledge. Businesses located in areas with fast, reliable network connections will have a competitive advantage over businesses located in areas with poor or no connectivity. Rebates for domestic solar panels favour homeowners with the capital to purchase and install the panels. Such homes then have lower power bills at the expense of homeowners unable to afford the initial capital investment, and of renters, contributing to financial inequality, see Appendix Bottling sunlight: energy storage technologies [930]
6.	Equality	Economic scaling improves access to technologies Technologies which improve access to financial opportunities, education, health and medicine, physical access	Widespread availability of electronic media platforms promotes equality and diversity of information. Access to information, to a means of assessing it, and to a platform for diverse voices and opinions, compares favourably with that of the dominant mid–late 20th-century model of large media houses controlling the distribution of information, see [305,306] Assistive technologies: there has been much emphasis on improving internet accessibility, including through the Government 2.0 Taskforce. This work is still a work in progress, and much of it predates the explosion in mobile and convergent media. The development of guidelines and initiatives to cover these platforms should consider opportunities for improving social participation, work, education, and removing or reducing barriers. Online education has the potential to bring down the cost of learning, opening both formal qualifications and teaching to students in lower socio-economic groups, or those for whom

			travel to a campus, or distance from it, may be problematic, see Appendix The education (r)evolution [764] Economic scaling and process innovation bring down the cost of production, which in turn reduces the price, allowing access to people who previously could not afford products. The rapid rise in popularity and reduction in price of desktop personal computers during the 1980s is an example of these phenomena. The wide availability and affordability of personal computers has improved people's digital literacy and opened whole new markets during the 21st century, see [305] Mechanical grinding and blending of nuts replaced the task traditionally carried out by daughters-in-law in West Africa (the machine was called 'the Daughter in Law who doesn't speak' by villagers). Because they are freed from the time burden of this task, girls now have the time to go to school, and women can start businesses [894].
7.	Trickle-down effect	Marketing Price reduction	During the second half of the 20th century the automobile ceased to be largely associated with luxury and the leisured classes and evolved into a mainstream means of transport, see Appendix Locked into the car. Appendix Bottling sunlight: energy storage technologies[930] See [305]
8.	Improved efficiency, effectiveness, and productivity	Mechanisation Domestic labour-saving devices Standardised processes Interoperability Scaling Process innovation, product innovation, service innovation, leading to production increase	Mass production in factories using robotics and automated production lines during the late 19th and early 20th centuries contributed to efficiency improvements, reducing the cost of production and improving productivity. Household changes such as the introduction of vacuum cleaners, easy-drying and non-crushable fabrics and improved household cleaners reduced the need for domestic workers, and mitigated the effects on domestic labour of women moving into the workforce. With scaling, cost per unit of output generally decreases as scale of production increases, because fixed costs are spread out over more units of output – examples are the rise of the business computer market in the 1960s, and the early success of the Ford Motor Company , see [305]
9.	Lower prices	Lower costs to manufacturer, scaling, mechanisation	3D printing's imminent 'Macintosh moment' (when mass-marketing becomes – apparently suddenly – feasible), see Appendix Printing the future? An analysis of the hype and hope of rapid prototyping technology[541]
10.	Lower cost of production	Adoption Scaling	Solar PV panels, see Appendix Bottling sunlight: energy storage technologies[930]

			3D printing, see Appendix Printing the future? An analysis of the hype and hope of rapid prototyping technology[541]
11.	Expanded demand	Product innovation Marketing Trickle-down effect	Desktop computing [305] Smart phones [305,306]
12.	Globalisation, rapid and distant communication, information dispersal, increased speed and distance of travel	Speed of travel Advances in ICT Pervasive infrastructure Gradual incremental technological change Mass adoption Reduced cost of travel Internal combustion engine Network effects – road and urban infrastructure in concert with cars and public transport developments	Companies in developed countries now have access to cheaper labour markets overseas – telephone help desks and call centres for telemarketing are often located in countries where labour costs are significantly lower than the labour costs in countries these call centres are serving [306]. Technologies for rapid and distant communication over time have included (but are not limited to) the telegraph, copper and submarine cables, the post, radio, airmail, telephones, television, radio, fibre optics, email, mobile technologies including smart phones, and the World Wide Web [305,306]. Over time, technologies for the dispersal of information have included (but are not limited to) the development of literacy, the replacement of scrolls with codices, the invention of the printing press, pamphlets, newspapers, and books, cameras, the electric telegraph, telephone, radio, television, the internet, email and the World Wide Web, and cloud computing [306]. The rise of planes, trains, trucks and automobiles has improved the capacity to move freight, information and people around the world quickly and over greater distances.
13.	New ways to store, process, organise, evaluate, and disperse information	Interoperability Data collection and generation Process innovation, product innovation Advanced computing capabilities (i.e. algorithms) Increased access to information	Towards the end of the 19th century, the punched card technology of Joseph Marie Jacquard's 1804 loom came to revolutionise information storage and retrieval, inspiring Herman Hollerith to devise an electronic tabulating system. Patented in 1889, the tabulating machine spawned a new industry in data processing. Built under contract to the US Census Office, the system provided a solution to the logistical problem of a data overload caused by the rapid population increase in the US during the 1880s. Hollerith's Tabulating Machine Company eventually merged with three others to become the International Business Machines Corporation – IBM. Punched cards were a mainstay of IBM's electronic computers well into the 1970s [305]. In the 1930s, HG Wells envisaged a 'world brain' or 'world encyclopaedia' as a centralised repository for human knowledge and collective memory. He anticipated that this would be based on microfilm, the breakthrough data storage and retrieval technology of the day, invented a century earlier but not effectively commercialised until the 1920s [306]. By the 1950s, IBM and its market rivals began to develop and market programmable digital

			general-purpose computers for business. This new tool for calculation rapidly evolved into a tool for data generation, analysis and storage [305]. In the 2010s, cloud computing and data centres present new options for storing and organising digital information. Capitalising on new ways to store and organise information and data often requires cultural change, involving process innovation or altering business practice, as much as technical solutions, and can be assisted by the development and adoption of standards. Since Hollerith's breakthrough tabulating machine 130 years ago, technologies for information collection, organisation, and storage have continued to develop apace. In 2001, the Australian Bureau of Statistics introduced an online form for the five-yearly Census of Population and Housing instead of a paper form, laboriously hand-delivered and collected. By the 2011 Census, 33% of Australian households chose to respond online. The ABS anticipates that by the 2016 Census, more than 65% of households will choose to complete their responses online. This process will streamline data processing as well. During the late twentieth and early twenty-first centuries, advances in computer modelling and simulation have changed what it means to understand a system [305].
14.	Reduced speed of travel	Tragedy of the commons Lock-in Path dependence	Road congestion, gridlock, see Appendix Locked into the car [765]. Land used for roads which could be used for alternative transport – e.g. trains.
15.	Controversy, opposing opinions, misdiagnosis, misplaced assumption of expertise	Widespread availability of information Inability to sort reliable informants from unreliable Risk perception Cognitive bias Cognitive dissonance Vested interest	Immunisation and GM crop debates: amongst widely accepted scientific evidence supporting the safety of these technologies, there is still strong and pervasive opposition by some members of the public, activist groups, and scientists. Belief perseverance and illusory correlation are common, see Appendix Genetically modified crops: how attitudes to new technology influence adoption [932]. 'Dr Google' effect: with the ready availability of medical information on the World Wide Web, users without medical expertise google their symptoms and make amateur diagnoses, potentially resulting in misdiagnosis. In related behaviour, having undertaken online research, some members of the public may dismiss genuine expertise and evidence in preference to their favoured explanations, and feel their views are vindicated due to confirmation bias, disconfirmation bias, and selective exposure, despite a poor understanding of the topic.

			In 2006 Toowoomba held a referendum on the use of recycled water for drinking. Once the proposal was made, the group Citizens Against Drinking Sewage got the 'first mover advantage' by promoting the 'yuck' factor and fear of health risks before the Toowoomba Council could get information to the community. In the referendum 62% of residents were opposed. Perception was a key factor in the opposition, as was mistrust of the treatment facility [514]. An anti-digit dialing league was set up in San Francisco when in the 1960s Pacific Bell switched from name+numerals to only numerals in the phone number: 'When Bell System executives grandly announced that all telephone exchange names would soon be replaced by seven-digit numbers in the name of progress, they presupposed the blind acceptance of a benumbed and be-numbered public. They were wrong: the telephone company is now facing a minor rebellion. In San Francisco last week the Anti-Digit Dialing League was incorporated to oppose "creeping numeralism"' [1047] . In 2013 the National Health and Medical Research Council commissioned a review on the health impact of wind turbines. The evidence did not support the claim 'that wind turbines have direct adverse effects on human health.' 'The criteria for causation have not been fulfilled. Indirect effects of wind farms on human health through sleep disturbance, reduced sleep quality, quality of life and perhaps annoyance are possible. Bias and confounding could, however, be possible explanations for the reported associations upon which this conclusion is based' [678]. Although the global medical community has failed to recognise or classify wind turbine syndrome as a disease, many anti-wind farm lobbyists and activist groups continue to claim that 'wind turbine syndrome' is a condition caused by living close to wind turbines [468].
16.	Lock-in, inertia	Sunk costs Vested interest Path dependency Market and policy failure Technological and institutional co-evolution Self-perpetuating Positive feedback Mass adoption	The rise of the personal automobile was accompanied by the development of infrastructure, laws and regulations including roads, footpaths, traffic lights, street lights, roundabouts, street signs, urban planning, road rules and conventions, that mitigate against the gradual imposition of a competing transport system. Economically, it would be prohibitively expensive, so stakeholders tolerate the costs associated with the current system (including fiscal, environmental, resource, opportunity, health and injury costs). The electricity grid: Australia's centralised, large-scale system of electricity provision is a historical artefact which allows a few companies to benefit hugely from of economies of scale and monopolies [1076]. In 1882, Edison introduced direct current (DC) technology which was challenged by alternating current (AC) backed by Westinghouse; both systems had benefits and drawbacks.

		Inertia at the level of corporate, government and system Path dependency (historical development of a given technological system) Mass adoption Vested interest	DC was more efficient but had a transmission limit of less than two kilometres. AC, when combined with transformer technology, allowed long distance transmission and the creation of large centralised power stations and massive distribution grids. DC would have been better suited to decentralised systems which are increasingly used as renewables increase [1076].
17.	Shock of adoption	Lock-in and inertia	IBM retained vacuum tubes in their business computers instead of moving to solid-state technology as soon as it was available. Similarly, the company retained punch cards for data entry, storage, and processing in their electronic computers in preference to magnetic tape, despite its effectiveness and availability. In both cases the retention of older technology was intended to shield the IBM's customers from the shock of adoption, and the company had a significant enough market share to be able to afford to retain these increasingly obsolete features [305].
18.	'Technological somnambulism' (Langdon Winner: lack of critical examination of the implications of new technologies by creators, users, and regulators)	Fashion Inertia	Refer to [306] Privacy – dataveillance and cybercrime implications
19.	Obsolescence (a measure of usefulness or fitness for purpose over time) Redundancy (an indication that an object or process is surplus to requirements, superfluous, or deficient)	Process innovation Product innovation Path dependence Technology substitution Late adoption, non-adoption Lack of demand Poor performance Obsolescence Technology substitution Convergence	During the 1940s and 50s in the computer industry, compact, solid-state devices like the transistor replaced cumbersome, unreliable vacuum tubes (invented in the first decade of the twentieth century), leading to much faster, smaller computers. These earlier computers are now obsolete, although vacuum tubes are still used for a number of other products, notably in the audio industry [171]. See [305]. Replacement of film cameras (and printed photographs) with digital cameras (with digitally-stored photographs): Eastman Kodak dominated photography for 100 years with a series of major innovations. The company filed for bankruptcy on 19 January 2012 as it 'finally succumbed to the digital revolution which left its products obsolete', announcing it would no longer produce cameras but would focus on printers (the company ceased producing film in 2009) [749].

	technology substitution	Adoption (of new generation technology), replacement of 1st generation technology with 2nd generation), convergence, fashion, product innovation, process innovation	Telebanking has rendered many traditional bank buildings and roles for workers redundant. As the camera components of smart phones improve, compact digital cameras are increasingly losing market share because consumers are increasingly use their smart phones and associated apps to snap pictures and record video: 'Why have a compact camera when an 8 megapixels iPhone is almost as good and it's always there in your pocket?' [749]. Examples of technology substitution include replacement of analogue colour television with digital flat screen; desktop and laptop computers with notebooks and tablets; replacement of mobile telephones with smart phones; replacement of an iPhone 4 with an iPhone 5; VCRs with DVD players; compact discs players with MP3 players (eventually to lose market share to smart phones), compact film cameras with compact digital cameras (eventually to lose market share to smart phone cameras).
20.	Disruption	Convergence Process innovation Product innovation Economic scaling	During the 1950s and 1960s digital computing significantly transformed fields of research, government, and industry which were dependent on complex and rapid calculation. But the true disruptive socioeconomic potential of general-purpose, programmable digital computers was not realised until the expansion of the personal computer market in the 1990s converged at the beginning of the 21st century with the growing pervasiveness of the internet and the World Wide Web in homes and businesses, increased network speeds, and mobile technology particularly in the form of smart phones [305,306].
21.	Adaptation for a purpose other than the one originally intended	Push and pull factors Consumer / user innovation	Augustus Gregory, then an assistant surveyor for the colony of Western Australia, reported on his expedition northward from Perth in 1848 that on the night of 31 October, a party of about 30 Aborigines 'stole our frying-pan to dig a well, but returned it next morning before the theft was discovered'. One man's frying pan is another man's shovel. The general-purpose programmable digital computer was initially conceived as an enormously powerful and fast, but essentially bespoke calculating machine. It has evolved into an essential tool for business and research, used to generate, process, analyse and store enormous quantities of data, for modelling and simulation, and to power near-ubiquitous information and communication technologies [305].
22.	Product, process and service innovation	Product and process innovations Process innovation ensues 'from the use of new combinations of tangible and intangible inputs', pre-existing or new, which are put to	'Product innovations may be tangible manufactured goods, intangible services, or a combination of the two. Examples of recent tangible product innovations that have had a very significant impact on the way people live and work are personal computers, mobile phones, and microwave ovens. Intangible products that complement these types of physical equipment include the various pieces of computer software needed to control flows of information through these devices, leading to the delivery of information, the supply of communication services, or the arrival of a correctly heated dinner' [442].

		commercial uses. It is 'preceded by inventions and succeeded by the widespread adoption of the new genre of products by customers, or the adoption of best-practice processes in the majority of firms' [442] Service innovation may be accompanied by, as well as causally related to, process and product innovation, as a new service will often require a new delivery system. Product development Customer demand	Henry Ford famously adapted the moving assembly line to allow the manufacture of automobiles. Adapting this process allowed him to manufacture, market and sell the Model T at a significantly lower price than his competition, creating a rapidly growing market [1100]. An assembly line mechanically moves parts to the assembly workers, then moves part-finished products from work station to work station in sequence until they are complete. This process allows workers, who each typically perform one simple operation, to assemble a complex product much faster and with much less labour than stationary methods which move the workers, tools and parts, see Appendix Locked into the car [765]. The punched cards of Joseph Marie Jacquard's 1804 loom, adapted for bus and train tickets in the later 19th century, inspired Herman Hollerith to devise his electronic tabulating system, patented in 1889 and used by the US Census Office, revolutionising information storage and retrieval. Hollerith's Tabulating Machine Company eventually merged with three others to become the International Business Machines Corporation, IBM. Punched cards were a mainstay of IBM's electronic computers well into the 1970s [883] [305,306]. New data infrastructures or gateways, for the Atlas of Living Australia or National Map (Section 7.7.6) Telework: working regularly from a place other than the office, usually from a home office, using ICT to connect to colleagues and work systems. There are a number of examples of service innovation, often accompanied by material technology, in the banking, finance and payment sectors. These include self-service points of sale at supermarkets; online shopping; physical payment systems including credit cards, automatic teller machines and EFTPOS; and virtual payment systems including PayPal, cryptocurrencies, and on-line banking.
23.	Commercialising leisure	Ubiquitous sensor networks Interoperability Dataveillance	Devices like smart watches, Google Glass and smart phones all provide users with a service, as well as providing operators and internet service providers with a source of data about what users do, who they talk to, their browsing habits, and where they go. Tourism apps for iPhone, iPad or Android.
24.	Labour-saving	Agriculture Civilisation Mechanisation Domestic labour-saving devices	Vacuum cleaners and dishwashers.

25.	Changing cultures of work		Although the use of mobile email offers flexibility and control of short-term interactions it also raised expectations of greater availability [660].
26.	Increased connectivity	Interoperability World Wide Web Mobile platforms Electronic social networking Wireless	The widespread use of the electronic telegraph and the rise of the automobile has lead to rapid increases in the speed of travel and of information, which are matched by an increase in global connectivity through electronic social networking (Facebook, email, and increased access to social networking and email on smart phones and other mobile devices).
27.	Changing social capital, commercialisation of social capital, changed values and expectations	Interoperability Electronic social media Ubiquitous sensing	Since the rise of widespread electronic communication and networked social media, concern has grown that 'traditional' social networks are breaking down. Some have blamed this breakdown on the rise of social media and other internet-based communication, but other evidence suggests that ICT, like other pervasive technologies, simply shifts people's ways of interacting with others. As people email more, letter-writing may decline. As people text and instant message more on their smart devices, voice calls and email may decline. As the physical distance between people is mitigated by increased electronic connection, people may be less inclined to join local social clubs, for instance, and choose to participate in online forums instead. The rise of electronic social networking may help to spread ideas, leading to lower face-to-face church attendance, or new models for college education which eschew formal campus attendance. However, human sociability as well as filter bubble effects [813] may see people remain as entrenched in old patterns of belief and behaviour within electronic networks as they may be in their physical neighbourhoods. Companies like Facebook, Google, and Yahoo commercialise social connections through collecting and analysing data generated through social networking on sites like Facebook, Google Plus or webmail. Advertisers use recommendations and browsing histories to promote products to others in the social network.
28.	New opportunities for costly signalling, rise of consumerism and materialism, changing expectations of standard of living and quality of life	Sexual selection / sexual signalling Group selection Millions of years of evolution Fashion and marketing	Pilots rejected the 1961 Cessna because it was too safe and easy to fly, similar to early bicycles that did not fit with norms of masculinity [805,1143].
29.	Penalties of adoption	Early adoption Uncertainty	Costs and regulatory compliance (buffer zones) of GM crops, see Appendix Genetically modified crops: how attitudes to new technology influence adoption [932].

	Penalties of non-adoption or late adoption	Late adoption Market share	
30.	Creative destruction (Marx, Schumpeter)	Obsolescence Product innovation Social change	'Kodak has been obliterated by the creative destruction of a digital age. Like many of its competitors, it appears unable to make the transition into the 21st century. Five years ago, it was unthinkable that this American business legend would find itself in a bankruptcy position. Kodak was caught in a perfect storm of not only technological, but also social and economic change' [749]. Contrary to the popular myth, Kodak did not fail to anticipate the popularity of digital cameras, but its business model was premised on cheap cameras with expensive film and processing. While the company produced some popular, affordable compact digital cameras, its baseline was affected by a fundamental change in consumer behaviour: casual photographers do not print digital photographs nearly to the same extent that they printed analogue photographs, but Kodak made its money from printing, not from cameras.
31.	Structural unemployment (technological unemployment)	New technology adoption Appearance / disappearance of markets Improved processes Obsolescence	For centuries, technological change has been a pervasive part of society with significant effects on the nature of jobs and the number of jobs. There has been a dramatic adoption of new technology in the workplace and an increase in the number of people in paid employment. An individual may lose his or her job due to technology adoption by industry, but evidence does not support mass unemployment as an impact of technology adoption over generations, see Appendix Technology and work [868]
32.	Luddism	Structural changes in the economy leading to job losses or changes, which may be chronologically associated with changes in a technology or suite of technologies	See Appendix Technology and work [868].
33.	Changes to the chain of production Improved efficiency Changes to business practices Changes to output and market share	Globalisation Big data ICT Process innovation Product innovation Service innovation Productivity improvement	On-demand economy (e.g. Uber, Airbnb, Handy). Spreadsheets. Adoption of new ICT: a Finnish study in 1995 found that it took a great deal of time and effort for an employee to learn how to use the PC – the learning process took up to 25% time for many months. US study of 471 managers found computer anxiety was an important barrier to adoption of PC people were afraid they would damage the PC [894], page 419.

	Changes to labour input and output leads to capital saving and investment, changed profit margins, wage pressure / elasticity		
34.	Mass adoption, ubiquity, pervasiveness	Vested interest Bandwagon effect Network effects Lack of choice	Fax machine - the initial product needed to improve sufficiently and costs decrease to allow it to reach critical mass. Manufacturers agreed on compatible standards [896]. • 1843 Fax (recording telegraph) invented • 1948 Ultrafax • 1960s Xerox fax for sending photographs and documents (media use) • Telephone dialling allowed faster transmission • After Japan entered the market in the 1980s, the cost of the facsimile machine dropped from $8000 to $2000 in 1984. By 1993 the machines could be bought for $250. Critical mass took a while, rate of adoption increased in 1987 [894]. Other examples include motorised transport, fossil fuel use, telephone, internet and computers – software, hardware, storage devices.
35.	Skill bias, skill premium, skill shortage, skills and crafts disappear, generalists favoured, specialists favoured, outsourcing	Mechanisation Structural unemployment Rapid technological change in the market Mechanisation Structural unemployment	Technology needs maintenance, control, policing; e.g. water systems, nuclear power. Maintenance can cost much more than the technology itself; e.g. maintaining electricity network and roads is more expensive than building it. Nowadays repair and service can cost more than the original item. This leads to greater consumption of new goods, and the loss of skilled repair people [321].
36.	Hazards: Air and water Pollution Toxic by-products Soil degradation Groundwater contamination	Tragedy of the commons Poor or no risk assessment, lack of foresight Conflicting resource use	Car use, see Appendix Locked into the car [765]. Nitrogen and phosphate rich run-off from fertilised crops. In Finland the Skolt Sami herded reindeer, used the hides and sold surplus meat; prestige was accorded to men who had good strong reindeer; family status matched how many reindeer a family owned; reindeer were special to Sami and important in their culture. In 1961 a school

	Extraction and depletion of water resources Loss of biodiversity or habitat Cumulative impacts (e.g. Global climate change, ocean acidification) Rise of superweeds Animal cruelty, reduced carrying capacity	Modifying the genomes of crop species to resist weed-killer	teacher purchased a snowmobile for recreation but soon found it useful for chores like moving wood and herding reindeer. Rate of adoption was rapid; by 1971 almost every one of the 72 households in the village had at least one snowmobile. The noise and smell of the machines drove the reindeer into a wild state. The friendly relationship between the people and the animals changed, stressed and frightened reindeer bred less so fewer calves were born, and more reindeer were caught and killed because of the access the snowmobile afforded. The average number of reindeer to each household dropped from 52 to 12 from 1961 to1971 [894]. The insecticide DDT is used to reduce populations of mosquitoes, which are vectors for dengue fever and malaria. In India alone in the 1940s, 75 million people were infected annually with malaria and 800,000 died of it each year. Sardinia in Italy had a serious epidemic, but at the end of a five-year spraying campaign (1945–1950), the number of malaria cases dropped from 10,000 annually to four in 1950. The World Health Organization program for global eradication saved millions of lives. But mosquitos started to become DDT-resistant. At about this time Rachel Carson's 1962 book *Silent Spring* was published, arguing that DDT was being used without consideration for the environment, in particular its impact on birds. The result was cessation of the WHO program [894]. Genes cross species from weed-killer resistant crops to closely related weed species.
37.	Waste generation and disposal, re-use and recycling, salvage	Tragedy of the commons Technological change leading to improved waste treatment	e-Waste, see [306]
38.	Extraction, use, and depletion of raw materials Improved resource discovery	Tragedy of the commons Product innovation Process innovation Scaling Demand	The petroleum industry: The capacity of geologists to 'see' underground has improved dramatically since the 1970s through significant improvements in digital computing and associated opportunities in modelling and simulation. For example, petroleum exploration has been revolutionised by massive improvements in the commercial production of legible 3D seismic images over the last 40 years, allowing geologists to 'look inside' Earth with much greater clarity than 2D profiles, making previously inaccessible petroleum reserves economic for exploration [873], see [305]
39.	Changes in energy use and efficiency	Process, product and service innovation, technology substitution	Changes in the use of coal during the Industrial Revolution
40.	Mitigating famine	Food distribution technologies Biotechnology	See Appendix Genetically modified crops: how attitudes to new technology influence adoption [932].

41.	'Meddling with nature'	Hubris	Refer to Appendix Genetically modified crops: how attitudes to new technology influence adoption [932].
42.	Restraint of trade Differential advantage	Early and late adoption Vested interest Lock-in	GM farmers have been accused of restraining the trade of organic farmers by 'polluting' their crops with GM pollen. The reverse has also happened: GM farmers have argued against the imposition of unreasonably large buffers, eating into their crops.
43.	Human health effects including injury, discomfort, or death Improving human health	Handling, inhaling, or ingesting infectious or toxic waste, hazardous chemicals, radioactive materials, or contaminated food and water Increasingly sedentary lifestyles Increased life expectancy Poor nutrition Accidents, explosions, machinery malfunctions, infrastructure failure Human error Weapons Side-effects of chemicals, drugs and medication Improved food security Improved nutrition	DDT, asbestos, mine run-off, agricultural run-off, industrial emissions. Mechanisation of manual labour tasks. People who would in the past not have survived to adulthood now die or suffer from age-related illnesses. Wide availability and distribution of fast food. Military hardware, bioweapons, drone strikes on civilians. Drugs like thalidomide, antiviral and antibiotic resistance. Drought or pest resistant crops. Golden rice (Vitamin A deficiency). Immunisation, antibiotics, surgery, diagnostic procedures and machinery, ergonomics engineering and infrastructure solutions. OH&S practices, safety features, road rules. Autonomous trucks in mining industry reduce human error.
44.	Metabolic effects	Mechanisation Increasingly sedentary lifestyles Virtual reality and computerised leisure activities	Increasingly sedentary lifestyles, accompanying increasing use of cars and the creation of a class of clerical workers who spend most of their days seated, is associated with the rise of a suite of disorders termed 'metabolic syndrome'. These disorders are implicated in stroke, heart attack, and type 2 diabetes.
45.	Changing understanding of what it is to be human	Developments in biotechnology, cybernetics, artificial intelligence, ICT	Virtual reality and simulation; genetic engineering; increasingly intimate human–machine interfaces; AI, machine consciousness, machine 'personhood'.

	Transhumanism Potential social impacts of enhancement / gene therapy etc., i.e. Increasing or entrenching inequality Extended mind or physical capacity	Rise of literacy, printing press, personal computing, smart devices, Google Invention of stone tools	Invention of stone tools extended the capacity of hominids to hunt and butcher meat, and to prepare other food. These tools and the harnessing of fire may have resulted in significant social changes, as well as metabolic changes in early humans. Changes in the media of literacy and numeracy are associated with cognitive changes.
46.	Scientific breakthrough	Improved characterisation and fabrication technologies	Improved lenses led to invention and improvements in telescopes and microscopes (for the very big and the very small), contributing to the intellectual revelations of the Scientific Revolution.
47.	Regulation, legislation, standardisation Standard wars Patents	Public opinion Risk management Public safety Market failure Need for commercial certainty Intellectual property law Public safety e.g. OH&S Public opinion Empowering the consumer Market advantage / vested interest Regulation Reward for cost of R&D	Refer to Appendix Genetically modified crops: how attitudes to new technology influence adoption [932]. Regulation within the banking industry gave consumers access to information about foreign ATM charges. Regulation in telecommunications allowed consumers mobile number portability increasing competition in the market. E-cigarettes. Microsoft Windows. Seat belts in cars, other road rules, licencing regulations and conventions. Cochlear implants: By 1984 there was controversy around single vs multi-channel cochlear devices. While companies were following FDA regulations they were influencing future regulations and standards. The industry started a self-reinforcing cycle by developing standards to legitimise their own claims. This is not all bad since it can provide technical freedom to experiment. It is in the interest of private competing companies to cooperate to build the industry and the technical community and knowledge needed to sustain the industry. This can be done while simultaneously competing against one another. In the case of cochlear implant technology the 'first mover' advantage did not benefit 3M who were 'locked-in' to their single channel design. The followers were able to learn from the first mover's mistakes and rapidly introduce significant and advanced products [1086].

48.	Technopoly	Veneration of technology	A technopoly occurs in a society in which technology is deified, meaning 'the culture seeks its authorisation in technology, finds its satisfactions in technology, and takes its orders from technology' [850].
49.	Cultural impacts including disruption and preservation		Steel axes for Aborigines: Small nomadic tribe whose central tool was the stone axe, used for food and construction but also a symbol of masculinity and respect – only men owned axes. When missionaries distributed steel axes to the tribe they were well received because they performed better than the stone axe but they distributed them equally to women, children and young men. This disrupted the social status within the tribe [894]. Deaf culture produces its own set of beliefs, customs, art and language. Children who receive cochlear implants in early life have a greater chance of developing the neural processes needed for auditory processing. Some deaf people want to see more advances in technology that will help them live in the hearing world rather than treating deafness as a deficiency and something that needs to be fixed [501]. Digitisation projects preserve scientific and cultural heritage – for example, the Darwin Correspondence Project has digitised more than seven and a half thousand of Charles Darwin's letters (http://www.darwinproject.ac.uk/).
50.	Generational changes, including decreased value of elders as information resources	Information economy Internet Search engines	The information economy and widespread availability of electronic search engines can affect intergenerational relationships by undermining experience as a source of knowledge, thereby changing the dynamic between generations.
51.	Crime, including cybercrime	Poor or no security Improved tools for breaching security Poor or no encryption Corruption Online behaviour Inconvenience of taking and maintaining security precautions	Many people are victims to spam. In order for spam advertisements to be profitable, it has been estimated that 1 in 25,000 recipients need to open the email and make a purchase while the cost of spam is estimated in the billions in lost time, costly anti-virus tools and other preventive measures [25]. A study of spam and crime in Australia examined over thirteen million (13,450,555) spam e-mails captured in 2012: of the 492,978 found with attachments 21.4% were malicious, and of the 6,230,274 that contained a URL, 22.3% of the web links were malicious [13]
52.	Privacy, obscurity, secrecy, security, surveillance, espionage	Surveillance Ubiquitous sensor networks Interoperability	Terror powers for welfare fraud: 'The government routinely investigates welfare fraud using powers it originally sought to target terrorism. Centrelink now accesses more personal metadata than any other enforcement agency, more often even than the New South Wales Police Force. It's a simple procedure: a Centrelink agent fills in a form, gets approval from

		Paranoia by state intelligence agencies	elsewhere in their department, and is authorised to tap into personal phone records and email history. The subject is not informed' [208]. Some attempts at rearranging household functions e.g. laundromats vs machine, childcare, servants but the private ownership of tools and allocating housework to women created a large market for individual goods. Cooperative kitchens were trialled but how to do a number of people agree on what to eat, the standards etc. 'People want to live in their own homes with their own relatives, rearing their own children, regularly sitting down to meals together, decorating their own house, dressing themselves, controlling their tools'. Privacy and Autonomy often win over technical efficiency and community interest [219].
53.	Changing relationship of government to citizens Changes in participatory democracy Democratic deficit Resistance Civil disobedience		Arab Spring, new media, social networking, clicktivism, hacktivism.
54.	Access to services		Disability standards for premises with a provision for wheelchair access in buildings. This is also beneficial for prams, the elderly, tradespeople. Another example of a widely adopted standard is the raised dot on the #5 button of phones, keyboards, and ATM machines for the visually impaired [476].
55.	New forms of corporate and bureaucratic organisation	Business innovation, service and process innovation	Operations research applies advanced analytical methods, modelling and simulation to help businesses, industries, research disciplines and government agencies optimise solutions to complex problems [172] [305].

Appendix 2: Case studies

The project, *Technology and Australia's future*, delivered a set of working papers on various topics illustrating the socio-technical factors at play in the emergence and adoption of technology. These papers are available in full at http://acola.org.au/index.php/new-technologies-contributing-reports. A selection of these working papers are summarised in the following pages.

C.1. Printing the future? An analysis of the hype and hope of rapid prototyping technology

Overview

- 3D printing has recently attracted a wave of mainstream attention as cheaper, consumer-targeted devices have become available. These 'domestic' printers are significantly less sophisticated than those used in manufacturing, usually dealing in low volumes of single-material plastic.
- A spectrum of new use and users have emerged over the last three years as a result of cheaper, smaller scale consumer-friendly devices that offer site-specific, real-time, print-on-demand customised systems.
- Opportunities for users to experiment with this new technology and 'try before they buy' is currently relatively limited in Australia.
- 3D printing requires a constellation of skills and contingent technologies
- The widespread ability to scan and reproduce physical objects raises. IP/copyright concerns mirroring those of digital media piracy and concerns (for e.g. the fabrication of weapons).
- Rhetorics of transformative change have pushed the technology near its peak of 'inflated expectations' – the hype currently does not match the market or reality of use.
- The domestic 3D printing market currently lacks a 'killer application' – a strong social need that would drive the technology beyond the stage of novelty in the same way that the use of social media drove the uptake of digital photography.

Introduction

The term '3D printing' applies to various processes that are used to create physical objects in three dimensions from a digital model. The technology has existed for 30 years, but there has recently been a shift in accessibility and uptake in the market. Consumer hopes have been inflated by hype around the potential to transform markets and business practice, but to date the technology has not delivered as expected.

Traditional uses of 3D printing

A 3D printer is a machine which can rapidly turn a design on a computer screen into a physical artefact by depositing material in layers to build up an object in three dimensions.

3D printing is not new. The manufacturing industry has used this technology since 1984 (engineers usually call the technology 'additive manufacturing' rather than 3D printing). 3D printing has accelerated product development in the aerospace and automotive industries by enabling computer-aided design models to quickly produce plastic scale models, a process known as rapid-prototyping. The technology now also enables 3D printing of metal objects, which allows manufacturers to print metal products directly.

[Box 1: Selected types of 3D printers]

Stereolithography This is the original form of 3D printed invented in 1983. A pattern is drawn on a liquid polymer with a beam of UV light that solidifies the polymer. Repeating this process layer-by-layer can make a 3D object.

Fused Deposition Modelling A polymer filament is heated and extruded through a nozzle, like piping icing onto a cake, and used to build up a 3D object. This is the most common and cheapest form 3D printing, and is used almost exclusively in desktop machines marketed to consumers or small businesses.

Selective Laser Sintering A layer of powder is selectively fused by heating it with a laser beam. This process is high-end and expensive (a single machine can cost upwards of A$1 million) and can be used to create intricate 3D objects from various metals including titanium.

Changes in the market

- With the expiration of key patents over the past five years, 3D printing devices have become cheaper, smaller in scale and more easily accessible to individuals outside large-scale manufacturing.
- The price of desktop, consumer-friendly 3D-printers has dropped to as low as A$500, though most cost A$1000–2000. These devices are not yet mass marketed, but appeal to early adopters (e.g. DIY hobbyists), designers, artists and small businesses. Such printers take about 30 minutes to print a mobile phone-sized object, and print only plastic.
- Knowledge of computer-aided design is no longer necessary for 3D printing, as digital models of many common objects are available via open-source repositories e.g. Thingiverse online repository contains more than 100,000 designs – with this number growing rapidly.
- Large technology distributors are becoming retailers for 3D printers and services, and dedicated stores are also springing up. Wider access to 3D printers is also becoming available through knowledge-sharing communities (e.g. DIY collectives or maker-spaces). Australia's first Fab Lab, a collective maker-space, opened in Adelaide in 2012.

Mass market potential

The major selling point of desktop-sized 3D printers is that they can quickly create custom 3D objects that would otherwise be costly, time-expensive and require a skilled craftsperson to achieve.

Economies of scale

Some analysts argue that 3D printing undermines some traditional economies of scale that underpin mass manufacture. With 3D printing there is no premium on complexity or variety, there is less wastage of materials, and it is possible to 'print on demand' when a product is ordered.

Michigan Technological University research showed that household 3D printing of many common items (e.g. shoe insoles, shower heads, phone covers) is cost-effective compared with purchasing mass produced items.

Environmental impact

Proponents argue that because 3D printing can create objects on-site, this could reduce the often hidden costs of distribution and supply chains, as well as the environmental impact associated with the transporting of goods around the globe.

On-demand customisation

3D printers can be used to create personalised high-end products. For example, the Perth bicycle business Flying Machine uses 3D printing to create unique bicycle geometries tailored for each individual owner's size and riding style.

Innovation

3D printing has the potential to reduce the cost of small-scale manufacturing by reducing the barriers to entry for new innovations. Independent inventors have used 3D printing to produce low-cost solutions to problems, such as the Robohand prosthetic limb.

[Box 2: Some applications of 3D printing]

- design/fashion: jewellery or clothes with complex shapes that could not be made by other means
- food: some high-end restaurants/patisseries are beginning to 3D print confectionery and cakes from sugar or chocolate
- health: medical implants, such as hip replacements, can be created to precise specifications as defined by CT scans of the patient
- military/aerospace: some fighter jet components can be manufactured more easily using 3D printing of metals; NASA has successfully tested 3D-printed rocket engines

How existing practices shape new technologies

Ecologies of use

3D printing is nested within a larger network of forces. It cannot be extracted from the ecosystem of computation, digital literacy, manufacturing, distribution and a variety of installation protocols.

Transition to the home

Though there are other examples of commercial technology transitioning into the home (e.g. desktop printing, digital photography) it is unclear whether the necessary social niche exists for 3D printers to make the same transition. Digital photography, for example, has been successful because it fits into, and feeds, a larger complex visual culture through mass online communication.

Just because we can, will we?

Providing consumers with the opportunity to create 3D objects on demand does not necessarily mean they will do so. Bread-making machines enabling people to easily bake cheap, high-quality bread have been on the market for years – yet they are not in every home.

The design skills-base

A 3D printer is a tool. It is not a magic piece of technology that produces ideas. Rather it is a design method that relies upon a larger ecology of context, problem identification, technologies and skills. The user must possess a base set of skills to make effective use of the technology.

Two tariff model

Domestic use 3D printers are marketed under a two-part tariff model (similar to desktop inkjet printers), where a relatively cheap device is bundled with expensive consumables. The 3D printing consumable (filament plastic or resin that must be loaded to print an object) is driven by company profit and sold at a price premium that ensures long-term sales.

How marketing practices can influence the perceived demographics of users

The way in which key voices in 3D printing (e.g. Makerbot) communicate and represent the technology tends to attract and reinforce a particular target audience. Product designs and marketing strategies, for example, give the impression the companies are influenced by sci-fi, gaming and military iconography. This may have the effect of reinforcing stereotypes of technology users and influencing what kinds of people may participate.

Adoption in Australia

Despite the influence of these existing practices, Australia is not a blank slate for new technologies. There is the opportunity to shape 3D printing for an Australian market, and not just adopt the discourse and use from other places. A study of 3D printing in Australia, as it emerges, offers a chance not only to observe and understand but also to intervene in what shape it takes.

Rhetoric and hype

Like other new digital technologies, 3D printing is imbued by a rhetoric of radical transformative change (*The Economist* magazine has referred to it as the onset of a 'third industrial revolution'). Consumer expectations for new technologies often follow a well prescribed pattern of hype and disillusionment before their maturity as a practical product. In 2012, Garter Analysts placed 3D printing firmly at its 'peak of inflated expectations'. For comparison, virtual reality was placed in the 'trough of disillusionment', while speech recognition (now recognisable in applications such as 'Siri') was placed on the 'plateau of productivity'.

In response to the hype, some analysts have pointed to the technological limitations governing the usefulness and impact of desktop 3D printers in households. For example, these machines can print only plastic, yet most of the objects in our lives are made up of multiple materials. As the market expectations for 3D printing currently far exceed economic and productive realities, it is expected that consumer disillusionment will set in in the near term. The Gartner forecast is for the technology not to reach mature productivity for at least 5–10 years.

According to some critics, 3D printing has garnered attention based on its novelty value, rather than for any practical use. They argue the technology is still in search of its 'killer app' – an application that is so desirable it drives uptake of a new technology in the mainstream market. Until its killer app is found, some analysts are sceptical of whether domestic 3D printers will be widely adopted.

Despite forecasting the limited practical use of 3D printers in the home, some analysts argue that 3D printing will still have a significant impact in low-volume, high-end manufacturing, for example in the aerospace, medical and dental fields. 3D printing may also change the way in which small-scale businesses innovate. For example, 3D printing enables businesses to respond to demand rather than be caught out by the ebbs and flows of traditional forms of production and distribution. In this vein, 3D printing may catalyse disruptive change not only in terms of what is made but also in how businesses operate.

Regulation and IP

The widespread ability to scan and reproduce physical objects raises intellectual property (IP) and copyright concerns which mirror those of digital media piracy. Though regulators could clamp down on design files and open source information sharing, government must be wary of 'moral panics' that could crush entrepreneurial potential.

An alternative model is provided by Chinese political support for grassroots communities and individuals – large-scale manufacturers are collaborating with small independent makers and entrepreneurs and encouraging a combination of 'trickle-down' and 'trickle-up' innovation.

[Box 3: Case Study: The 3D printed handgun]

In 2013, Cody Wilson, a University of Austin law student, made available online the plans for a 3D printable handgun. The release sparked fears that 3D printing could reduce the barrier to production, thereby reducing the impact of existing gun control. The 3D-printed weapons, made in plastic, could also be invisible to current detection systems.

Though fears surrounding Wilson's design have abated (when the NSW police force experimented with it, they found that current 3D printed handguns may pose more danger to the maker of the gun than to anyone else), the release continues to be debated. Wilson's argument that his aim was to 'disseminate a printable gun design online, not print guns *per se*' has challenged conventional regulatory control given the weapon is distributed not as an object, but as a series of plans and instructions.

3D printing in Australia

Opportunities

- 3D printing has the potential to affect a range of Australian businesses. It potentially offers a way to mitigate the logistical issues arising from Australia's geographical and economic situation, such as the tyranny of distance, complexity of supply chains and rising costs. While 3D printing offers to manifest objects at the site of printer, it will not solve all the problems of distribution and production, because the raw materials still need to be distributed, and the printers themselves will not be implemented evenly across Australia.
- Australia is, in some respects, well suited to adoption of 3D printing as it fits with the Australian landscape and global position, and with ideas of national culture and identity (e.g. hands-on, DIY, experimentation and making-do). The first Fab Lab has proved a successful model for exposing diverse publics to 3D printing.
- Australia has had experience in industrial additive manufacturing since the 1990s, and this could be reappropriated for new and innovative use. According to the 2011 Wohler report, additive manufacturing has the potential to increase Australian production and export of high-value products.

Barriers to adoption

- In other respects, barriers to the adoption of 3D printing remain. As with any new technology, a user must possess skills to adopt the new technology. More specifically, adoption of 3D printing also requires a base knowledge of skills and infrastructure which may be currently limited, such as the ability to use computer design software, as well as access to materials, electricity and the internet.
- In the broader consumer market, access to 3D printers is more limited in Australia than in other countries such as the USA and the UK. As of early 2014, there was only one main distributor of desktop-scale 3D printers in Australia (Officeworks), and it was cheaper to buy and import from overseas.
- To achieve the promise of 3D printing's bridging of distance and resource accessibility, the uptake of 3D printing in remote regions may require government interventions akin to those seen with internet accessibility and electricity service delivery, such as subsidies, mandates and/or enhanced offerings. The adoption of technology follows a well established pattern that may be informative for how 3D printing will roll out in Australia.
- 3D printing is nested within a larger constellation of forces. It cannot be extracted from the ecosystem of computation, digital literacy, manufacturing, distribution and installation.

Conclusion

3D printing has the potential to affect a range of Australian businesses and not-for-profit community groups. The trajectory of past technologies is informative for how 3D printing might roll out in Australia. A study of the use of 3D printing and analogous technology could inform how it will be adopted. The role of the collective maker movement in Australia, compared with other countries, will also need to be understood. If encouraged, new paradigms, such as the 'trickle up' innovation exemplified in China, could improve R&D. It will also be important to understand the industrial additive manufacturing infrastructures already in place and how these might be open to manufacture of high-end products.

Full working paper available at http://acola.org.au/index.php/new-technologies-contributing-reports

C.2. Bottling sunlight: energy storage technologies

Overview

- Electricity has transformed everyday life and the broader economy. But today, the electricity system faces huge challenges: ageing infrastructure, variable demand, and a need to integrate energy from renewable sources.
- Energy storage technologies can deal with today's uncertainty in the system, and give greater flexibility to deal with change in the future.
- Energy storage technologies can mean anything from a small battery to a large pumped hydro system. The different categories of energy storage technologies can make it difficult to predict, assess and regulate.
- Different storage technologies offer different benefits depending on the demand, transmission, flexible generation and energy management needs. Assessment of the costs and benefits of storage needs to be based on the application, location and use of each technology at stages in the electricity system.
- The existing electricity network based on a *supply follows demand* principle will need to undergo significant changes in order to deal with the challenges it currently faces.
- The electricity network is embedded in institutional structures that lead to 'technological lock-in': an inability to make highly beneficial changes.
- There are a host of solutions to the many problems faced by today's electricity grid. There is no silver bullet technology, and there is no silver bullet solution.

Introduction

This paper uses energy storage technology as a starting point to better understand the complexity of the broader electricity system.

Although in use in Australia since the 1890s, energy storage has had limited use. The benefits of energy storage across all sectors of today's electricity network have only recently been appreciated worldwide. The pressures of variable peak demand, higher infrastructure spending, rising energy prices, and a focus on reducing emissions – as well as the falling cost of more efficient, affordable renewable energy technologies – is now driving the power industry to review the complex collection of technologies that make up our electricity system.

Outdated and under pressure

In Australia, local government bodies developed electricity supply in the 1880s. As demand grew, isolated local networks were interconnected and electricity was supplied from central power stations[47].

In most countries, grids were designed to generate electricity from fossil fuels, such as coal or oil, providing power via a centralised grid; this model has stayed largely unchanged for more than a century. Today, the centralised supply-follows-demand structure is reaching its limits on many fronts. For example the system is designed to meet peak load under fault conditions requiring extensive infrastructure and resulting in increased costs.

The electricity industry is now under pressure to revise this model due to higher energy prices and more efficient, affordable renewable technologies.

Old becomes new

For more than a century, electric power has been generated in real-time for immediate use, meaning that electricity power generation capacity must be capable of peak power demand which occurs only rarely. As a result the system is inefficient from an energy viewpoint. Energy storage enables the grid to operate on an energy (average power) principle rather than an immediate power principle hence allowing reduced generating infrastructure costs (because the peak demand can be met from stored energy) and also supporting a demand follows supply principle which then supports variable supply such as renewables.

Uncertainty: variable demand

Balancing supply and demand is fraught with uncertainty. Daily, weekly and annual cycles need to be catered for. The fluctuating nature of renewable energy sources has added a layer of complexity: while solar power can relied upon during hot spells – thereby compensating for summer peaks – it is not as reliable at other times; the same is true for wind power. Nevertheless, renewable energy is attractive as a sustainable resource. A reliable electricity grid requires the capacity to handle peaks on demand as well as provide a reliable supply over long periods. Energy storage technologies help deal with this inherent uncertainty and provide greater flexibility in the grid.

Pricing electricity: incentives and disincentives

The way electricity is priced in Australia will have an impact on the deployment of storage technologies. Current pricing could be said to encourage co-generation by consumers, but discourage storage by suppliers.

Charges to households are heavily based on the amount of energy used – even though almost half of the actual cost is due to the network (poles and wires), not consumption.

Suppliers can vary what they charge users based on the amount of electricity taken from the grid; but what they charge for poles and wires is fixed by the Australian Energy Regulator. This means that, as customers generate their own electricity, they contribute less to the *maintenance* of the network – even though they continue to use the network.

Energy storage options

Large-scale energy storage can come in various forms. The best known are batteries, an electrochemical technology, however, electricity can also be stored in many other ways, including flywheels, compressed air, hydrogen tanks and thermal energy vats (such as storing collected solar power in molten salts). Energy storage technologies are vastly different in design and application. Often, local conditions – such as demand, load, topography or distance from a grid – determine which technologies are the most efficient and economical to deploy.

There is no single 'best' storage solution that applies to all situations. It depends, on the needs and conditions of each situation. For example, flywheels are a good option for uninterruptable power supply, while compressed air can be a good match for renewable energy integration and load levelling.

Technology	Description	Main Challenges
Pumped hydro	This system uses two reserves to separate water vertically. Water is pumped uphill during off-peak time and released at peak times, the flow of water driving turbines. Pumped hydro is the main form of energy storage worldwide, its primary application being for energy management and back-up reserves.	Large capital cost involved in building facilities, geographic limit and environmental impact. Challenges: Large capital cost involved in building facilities, geographic limit and environmental impact.
Compressed air	Air is pumped into storage at high pressure and released at peak. During discharge, air is combined with fuel (natural gas) and	Geographic limit, slow response time, low efficiency and environmental impact.

	combusted, then passes through turbines. As the air expands, energy is released. Its primary application is for energy management, back-up reserves and can also be used for integrated renewables.	
Flywheel	Rotating mechanical device that is used to store energy. Its primary application is in load-levelling and frequency regulation	Rotor tensile strength limits and limited energy storage time due to high friction loss. If operated in a vacuum, the amount of friction is reduced, improving efficiency and reducing damage to device.
Batteries	Converts stored chemical energy into electrical energy, a reversible reaction that allows for recharge. There are many different battery types: lead acid, sodium–sulphur (NaS), and lithium-ion (Li-ion). There are also experimental battery designs for large-scale utility storage, such as vanadium redox flow batteries. Li-ion batteries can be used for power quality and frequency regulation.	For Li-ion batteries as an example: scalability, high production cost, sensitive to temperature. Vanadium redox batteries show great promise, but are still under development.
Fuel cells	A fuel cell converts chemical energy into electricity through a chemical reaction with oxygen or an oxidising agent, and requires a constant source of fuel. Primary application for power quality and energy management	Cost
Thermal	Allows excess thermal energy to be stored for later use. A range of technologies can collect thermal energy, each with their own performance and application characteristics eg. solar, heat or cold produced from heat pumps, geothermal, heat and power plants.	Storage performance stability and cost.
Superconducting magnetic	Stores electric energy in a magnetic field within a super-cooled, superconducting coil. It has high efficiency and fast discharge times, and its primary application has been in power quality and regulation	Low energy density and cost.
Supercapacitor	This is a hybrid between batteries and capacitors; supercapacitors store energy in the electric field between a pair of charged plates. The primary application is for load levelling and stabilisation, and they are capable of fast charge and discharge and have a long life cycle.	Cost

Because no single technology will meet all requirements for grid-scale storage, a range of technologies need to be developed.

Can Australia adopt new storage technologies?

In 2012, the Clean Energy Council concluded the adoption of new energy storage technologies is inevitable, and suggests Australia develop a range of technical and policy measures, such as technical and regulatory standards, to enable storage connections to the existing grid.

In July 2012, the CSIRO was contracted by Australian Energy Market Operator (AEMO) to study renewable energy supply, electricity generation opportunities and storage for the national electricity market. Findings include that solar thermal molten salt storage has significant opportunities; and that batteries are an attractive option, as they can be located in any site in a variety of configurations, and can be used for both balancing variable output from wind and photovoltaic plants as well as load-shifting (moving mass electrical charge from one part of the grid to another, usually to deal with peak demand).

Two key messages arise from these and other reports: a) energy storage is important in managing Australia's national electricity grid in the future; and b) there is no single 'best' energy storage technology option. Each choice is contingent on the specific problem being solved, and on the infrastructure and energy resources available in any given location.

Technological lock-in

The electricity network in any one region is a complex system of technologies that has evolved from historical decisions taken and technological paths chosen in response to existing technological infrastructure and the institutions that create, diffuse and employ them. Technological lock-in describes when technologies and systems are set on a path that is difficult and costly to change: it includes sunken costs from earlier investments, vested interests, learning gained through use which cuts the cost of products, reduced uncertainty in the market and network effects. Hence, an existing system will continue to be favoured, even when superior substitutes arise.

This can lead to a 'lock-out' of new technologies, such as renewable energy, forcing new options out of the market or acting as an entry barrier for new businesses. Energy storage systems will become an important factor in dealing with the evolving electrical energy system.

Vested interests and innovation

Vested interest by existing operators is often blamed for the lock out of new technologies and businesses. But it is more than just interest groups and the lobbying of politicians that makes it so difficult to make change in a well-established system of users, makers, producers, distributors and governments. In a study comparing structural change and vested interests at play in the uptake of wind power in Norway (where wind struggled for support) compared with its Scandinavian neighbour Denmark (where wind was strongly backed), Espen Moe found five key indicators that a nation will favour vested interests and be less likely to overcome techno-institutional lock-in. They include a lack of knowhow; lack of support for entrepreneurship at the institutional level; government preference for cost effectiveness, which automatically benefits more mature technologies and industries; lack of a social mandate from the public; and the existence of active vested interest groups [700].

The study found that old industries – and the structures around them – could therefore unwittingly obstruct new entrants into the market due to the social, structural, legal and political forces. The longer an industry is in existence, and the more the country depends on one or a few industrial clusters, the greater their dominance and impact.

Using niche markets to accelerate innovation

Robin Cowan describes six events that need to occur to overcome existing lock-in: a crisis in the incumbent technology, regulation, technological breakthrough, changes in taste, creation of a niche market and/or scientific evidence.

Inertia created by technological lock-in and vested interests requires a new technology to preform dramatically better than the old. And new technologies often come from niche entrants. Hence, niche markets are an attractive policy target: dominant players are not interested in defending them, and new entrants are keen to succeed in a niche market as a precursor to larger penetration. Costs fall substantially after an extended period of testing, learning and other improvements. Widespread adaptation follows a period of experimentation where the technology is tested, refined and adapted.

Picking a technology winner or solving the problem?

No one can predict which storage technologies will become leaders; hence, regulating to encourage competition among technologies allows the market to breed innovation, and avoids prematurely locking-in a technology that may later prove less useful. Creating an environment that encourages experimentation is essential.

Reports by the Grattan Institute on energy policy show that, over time, this will be the cheapest way to deploy optimal technologies and get the best results. Governments that legislate for an ultimate end-goal (e.g. putting a price on pollution) allow businesses to determine how to achieve that goal, and minimise the need to predict the future as well as giving businesses certainty and flexibility.

Conclusion

Escaping lock-in of pervasive and complex systems is possible. Past examples include the transition from the vacuum tube to transistor to integrated circuit for electronics; from canals to trains to trucking for the transportation of goods; and from fixed phone to the wireless phone. These transitions require changes in technology performance and cost, but also government, social, legal and regulatory structures, which can take decades.

The future grid is likely to incorporate extensive sensing and control technologies alongside advanced metering infrastructure and will more closely follow a *demand follows supply* principle in order to cope with the variable supply nature of renewables. Energy storage technologies have the potential to deal with uncertainty in the electricity system and allow for greater flexibility to deal with change. Energy storage can improve system stability and efficiencies across the electricity grid. It allows household and commercial customers greater choice in meeting their energy needs. Storage also offers small and remote communities a viable alternative for electricity supply.

It is most important to note that no single storage technology will meet all the requirements of energy storage. A portfolio of storage technologies will be required to meet the needs of different applications, and suitability will depend on key energy storage parameters such as energy density, power, charge rates, discharge rates and lifecycle.

Full working paper available at http://acola.org.au/index.php/new-technologies-contributing-reports

C.3. Collective technologies: autonomous vehicles

Overview

- The autonomous vehicle is a collective set of technologies made from parts assembly. Autonomous features have been added to cars gradually over the decades and the trend is likely to continue.
- Predicting diffusion and adoption of autonomous vehicles is difficult because of the multitude of individual components that need to be developed within their own socio-technical complex.
- Information and communication technology (ICT) is a key enabling technology for automated driving. It is key for in-vehicle components, mobile devices and smart infrastructure.
- Historically, safety features have taken around 30 years to be fully adopted in cars. Comprising multiple components of autonomous technology and infrastructure, the driverless car is likely to take longer.
- Some functions of an autonomous navigational system can be achieved without in-vehicle automated features. Smart infrastructure and a smart device (such as a phone) in a car could achieve the same outcome.
- As cars become more autonomous they can be regulated with the gradual adaptation of legislation, regulations and safety standards, which can speed adoption. A fully automated system however may require more significant change.
- The development, adoption and use of autonomous vehicles will depend on a multitude of socio-technical decisions made along the way.

Introduction

The convenience and independence cars provide has made them an integral part of our society, it has changed the way we live and work. Many people love to drive and see their manually operated car as part of their identity and a status symbol. But the car does come at a cost. Autonomous vehicles are greatly anticipated because of their potential to reduce car accidents, traffic congestion and pollution. However widespread adoption of technology will depend on how people respond to the introduction of more automated vehicles and more crucially on the development of each individual component that makes up the autonomous vehicle.

Dangerous, polluting and time consuming

Australia is a nation of drivers. The country has 13.3 million registered passenger vehicles and close to two to three people drive to work each day. Unfortunately, along with the benefits they bring, cars also come at a serious cost. In Australia, road accidents killed 1193 people in 2013 and cost an estimated $27 billion each year. Though death rates continue to decline steadily, loss of life and hospitalisations due to road accidents are still substantial. Australia’s passenger vehicles also contribute to carbon dioxide emissions and, by releasing small particles into the atmosphere, indirectly kill marginally more people than road accidents. Road and parking infrastructure too is under increasing pressure, with car numbers in state capitals set to increase by around 23% by 2020, worsening congestion and decreasing productivity.

Collective technology: a parts assembly process

An autonomous vehicle requires a range of technologies to sense and monitor the behaviour of its external environment and to take action where required. A driverless vehicles such as Google’s self-driving car is an innovation that brought together existing research and technologies from a broad range of disciplines and sectors:

- A combination of sensors, used to make sense of the external environment, gather information regarding distances to other objects and allow vehicles to more accurately pinpoint their location.
- Processing data captured from sensors to make decisions and manage the interaction between the human driver and computer.
- Interlinking that with mechanical control systems that perform the desired action of braking, accelerating, turning etc.
- Communication and networking technologies are needed e.g. vehicle to vehicle, vehicle to infrastructure, pinpointing location.
- And for a fully autonomous system, smart infrastructure is required to provide a feedback loop of data to inform optimal decision making.

Each of these technologies need to develop and succeed within their own socio-technical environment – they need to advance their technical performance, they must become affordable and survive the market, and they must meet standards and regulations that ensure their interoperability. For example, a driver monitoring system must bring together cameras, sensors, eye tracking software and the braking control system.

How quickly new features appear in cars will depend on a multitude of complex, interdependent factors including technological advancement, market dynamics, cost and regulation.

Enabling technology: ICT

The development of autonomous functions is highly dependent on ICT e.g. sensors such as lasers, radar and 3D cameras, sophisticated data processing analyses observations. The cost of electronics in luxury cars can account for 23% of total manufacturing costs and an estimated 80% of innovation in car manufacturing is now attributed to electronics.

The autonomous vehicle is an example of how ICT has become a general purpose technology and in particular its ability to complement existing vehicle technologies to offer a new function in personal mobility transport. In all autonomous features, information and communications technology (ICT) will continue to be the key enabler. ICT makes it possible for automated functions to be added onto the existing motor vehicle and existing transport infrastructure or to address the problems in other ways that are not necessarily embedded in the vehicle.

The promise of the car that drives itself: treat predictions with caution

The introduction of advanced autonomous technology is exciting. Advancement to driverless cars, with the profound benefits they can bring to individuals and society has attracted a lot of attention in the media.

Recent predictions are that the cars will be driving themselves off dealership forecourts between 2035 and 2050. However, predicting the success of a technology made up of a multitude of independent components is particularly difficult.

As early as the 1950s, General Motors declared a 20-year wait for driverless cars. Arguably, these optimistic estimates from industry could be due to optimism bias (experienced by insiders in most industries) or self-interest. Academia however is more conservative. While much of the basic technology is available and advancing quickly, there is still a long way to go to improve quality, performance and affordability.

Predictions often assume revolutionary development and adoption rather than the incremental changes seen in the past. Compounding the issue, technology that prevents harm tends to be adopted slowly. For instance, it took 30 years for 90% of Australian cars to adopt seatbelts for all occupants, despite progressive regulation of compulsory seatbelt use.

The technical challenges

For all their faults, humans are more sophisticated processors of information than any computer, and driving is a complex task. Replicating such sophistication artificially presents a major challenge requiring long-term R&D. Achieving this in an affordable product is harder still. For instance, the Google car uses a $70,000 LIDAR-based system – a laser 'eye' – for a 360-degree view of the road. It's uncertain how much its cost can be reduced. A radical redesign may be required and it could be overtaken by other technologies.

Technological progress is needed in the field of sensors and artificial intelligence. Complex algorithms that can process the external environment in real-time, make the appropriate judgement, and follow through with the correct action are required for automated tasks. Technology that enables autonomous cars to deal with these complex situations could take a long time to become affordable and compact enough to be included in commercially available cars.

Much of the hype associated with autonomous vehicles is based on an overestimation of what is actually possible with the technology. Some commentators take it for granted that 'strong AI' is just around the corner. But interaction between the driver and the car is a particularly difficult problem. As cars increasingly take charge, drivers become disengaged from driving, making them less capable of intervening when needed. Skills are also lost through lack of practice – the so-called 'irony of automation.' The effects have been seen in pilots in airliners and in the first Google cars. The cars have steering wheels that enable intervention in an emergency, and while there were no crashes, drivers were distracted and slow to respond when needed, Google engineers told the *New York Times*. Google's solution is to develop a fully driverless car. For them and other manufacturers, complete removal of the driver will increase the complexity of the technology, as it will need to handle all possible road scenarios safely with no on-the-spot help from a human driver.

Wider implications

Implications of the driverless car go further than safety, congestion and pollution. Fully autonomous vehicles currently operating include driverless trains, unmanned autonomous vehicles (UAVs) and planes operating on autopilot. In the Australian mining industry, Rio Tinto is one of several companies using driverless trucks that can operate 24/7. Other sectors that could benefit from increased automation include agriculture, space industries, military and public service operations such as disaster management and border patrols. Employment for professional drivers including taxi and freight drivers may decrease while car rentals and sharing could become more popular than private ownership, particularly if vehicle costs are high.

For individuals, potential benefits include increased mobility for children, the elderly and adults whose disabilities prevent them from driving; for the first time independent car travel could be accessible to the blind and visually impaired and people with dementia and reduced mobility. Time that would otherwise be spent driving could be freed up for work, reading or sleep, similar to time spent commuting on public transport. Stress levels could also drop and road rage could become a thing of the past.

Regulation can speed up adoption

Radical changes in regulation are not typically needed as new technologies become available. Autonomous cars are not likely to be any different. Existing autonomous features and the liability of drivers, manufacturers and retailers can be regulated within legal frameworks. Already, California, Nevada and Florida allow driverless cars on their roads, with conditions. In California, they must have a driver who can take control, if needed, preventing Google from testing their steering-wheel-free car.

One key challenge is accident liability: when autonomy increases, there is a shift of responsibility from the driver to the manufacturer. Studies by the RAND Corporation, a non-profit global policy think tank, recommend safety standards to buffer the impact on the industry. Liability can also be reduced with the collection of data. Black box recorders have proven valuable in aviation and could be adopted in cars.

Any standards and legislation need to take into account the many driving scenarios under which autonomous technology will be tested. The fatal consequences of a narrow approach were seen in the US, where from 1990-2008, 291 deaths were caused by airbags. Because the standards were specified for the protection of an unbelted male adult in a head-on crash, the technology resulted in excessive harm to smaller people, for whom the technology was not optimised.

Handing control to a computer

From the electric kettle to robots used in surgery, people usually come to accept automation over time. Depending on the application, autonomous technology can provide convenience and improve safety. Surveys reveal widespread acceptance of the gradual introduction of individual autonomous features in cars. However, they also indicate a significant proportion of the public would feel unsafe in a driverless car.

On a basic human level, handing over control to a machine can be perceived as a risky thing to do. Some anxiety may stem from language and its interpretation. 'Autonomous' defines technology that carries out tasks normally performed by humans, without supervision. Some people might associate this with uncontrollable and consequently dangerous cars with minds of their own. Such perceptions can slow or speed adoption directly; indirectly, they can drive policies and regulation that do delay the development of the technology.

Autonomous cars also raise an ethical issue. To account for emergencies, a driverless car's actions must be decided upon and defined in advance, using rules programmed into the technology. Dilemmas include whether the safety of passengers in one car should be sacrificed for the safety of others if it minimises the overall harm in an accident. And if something goes wrong, with multiple technologies employed, who is to blame?

There is no one solution

The benefits and costs that come with cars on the road cannot be simply attributed to the car itself. It's about the use of the car: how, when and why we drive our cars. Cars must be understood as one part of the broader socio-technical complex of personal vehicle transport. Autonomous cars are one of a range of solutions that can potentially reduce the negative impacts of cars on our society; others include regulation, pricing mechanisms, improved public transport, access to bicycle paths, and addressing driver behaviour.

One way to tackle congestion and pollution is to take cars off the road by introducing measures like teleworking, improving public transport and congestion pricing. Research by the University of Sydney's Institute of Transport and Logistics Studies predicts that a charge of 5c/km in the Sydney would result in 22% of commuters driving outside peak periods and 13% switching to public transport. Short-term car rental – or car sharing - is still in its infancy in Australia, but the industry is growing and could also cut down congestion.

Let's not forget the key problems we want to solve: road safety, congestion and pollution. Non-technical solutions and solutions that are not necessarily in-vehicle technologies have the potential to help solve these problems too.

Conclusion

Death and injury that result from car crashes, carbon dioxide emissions and traffic jams are negative consequences of the vehicles on Australia's roads. There are a range of ways to reduce these, including laws that enforce speed limits, technology that prevents drink drivers starting their cars and measures such as teleworking that reduce cars on the road. Cars with autonomous driving features and the driverless car in particular are one technological solution.

Autonomous features have been added to cars for decades. Today, several advanced features are available including forward collision avoidance systems and parking assist technology, reducing accident rates. The driverless car is made up of a collective set of autonomous features, with potential benefits that go further than improvements in safety and reductions in pollution and congestion.

The adaption of laws, regulations and standards provide a way to maximise safety and the other benefits of autonomous cars, as responsibility shifts from the driver to the vehicle. Changes are unlikely to pose a major challenge within existing legislative and regulatory frameworks.

Much of the basic technology to create a driverless car is in available, but tough technological challenges remain and several factors will dictate whether the public accept fully autonomous cars. Consequently, it is hard to predict how long it will take for all components to become market-ready and for the driverless cars to be widely adopted, if at all.

Full working paper available at http://acola.org.au/index.php/new-technologies-contributing-reports

C.4. Genetically modified crops: how attitudes to new technology influence adoption

Overview

- The name given to the emerging technology of 'genetically modified crops' contributes to hiding the history of plant breeding. Humans have been altering the genetics of crop plants for thousands of years.
- Genetically modified food crops might offer part of the answer to future global food shortages but the economic benefit gained from the use of genetically modified crops is highly dependent on location, environment and social practices.
- There is no scientific evidence that genetically modified foods are a risk to human health or the natural environment.
- Food is so fundamental to human survival that our attitudes to food technologies are often based on a suite of factors outside the realms of scientific evidence.
- Our uncertainty of approach to genetically modified crops encompasses fear of the new and unknown, which in turn influences its regulation and adoption.
- Public acceptance of genetically modified technologies would benefit from transparent and targeted communications that consider how meaning, values and beliefs shape attitudes.

Introduction

People have been modifying the genetics of plants to develop crops ever since agriculture began more than 10,000 years ago. During the past few decades, developments in biotechnology have enabled us to make improvements to the DNA of organisms. Crops produced through these relatively new techniques are described as 'genetically modified' (GM). The term ''genetically modified'' has a specific technical meaning: the precise, controlled and deliberate manipulation, insertion or deletion of genetic material. So far, researchers have developed GM crops in order to increase yield, improve food quality and reduce the use of pesticides and herbicides. These crops have shown some agronomic success. No scientific evidence to date shows that they have adverse impacts on human health or the environment. Despite this, there remains some extreme public aversion to farming genetically modified crops and consuming their products.

Food security: GM crops are one part of the solution

One of the biggest issues facing the world is food security. Already, more than 12% of the Earth's population suffers from chronic hunger. The problem is expected to grow, with the United Nations predicting that the human population will pass 9 billion by 2050 – up by 6 billion in just 100 years. The Australian Centre for International Agricultural Research forecasts that global crop yields will need to increase annually by 1.1% to meet the world's predicted food demand in 2050. The centre supports crop intensification – bigger, better, more productive plants – as a way of delivering these higher yields.

Australia's relative affluence and social structure mean that we do not yet have a problem feeding our own population. However, food security is already of significance here because it's linked to political stability within the Asia-Pacific. It's also tied to other issues in our region that could affect food production, including trade, and climate and environmental challenges.

Genetically modified crops, with their capacity to improve yields and nutritional content, are thought to be an important part of the solution to food security. Achieving the level of crop yield increase needed to feed the world will still, however, depend on farmers adopting best practice in crop management and plant breeding.

From genes to grains

Every trait in a crop plant – from its leaf shape to the way it uses water – is controlled by a gene or combinations of genes on the DNA molecules of the plant cells. Well before this was understood by scientists, farmers were improving crop plants by manipulating and modifying crop genetic makeup through traditional breeding techniques: identifying, selecting and crossing-breeding plants (and animals) with desirable traits. Many modern crops differ greatly from the wild relatives they descended from. Some now require shorter growing seasons, have larger fruits or seeds, are more resistant to pests or disease, have higher nutritional content, or are better adapted to local environmental conditions.

Changing technology in plant breeding

Modern biotechnology techniques allow for an organism's own genes to be altered in a targeted way. They also enable specific genes to be transferred from one organism into another. Insect-resistant GM crops, for example, contain a gene from a soil bacterium that gives the plants their own inbuilt protection against insects, which means the amount of insecticide sprayed on a crop can be reduced.

Plant breeders continue to improve crops using traditional methods, but the science of molecular biology and tools of genetic engineering now provide the ability to identify and work with the specific genes responsible for particular traits. It means the process of crossing and selecting plants with desirable traits can be done at a significantly faster rate and with considerably more precision. This technology development provides the opportunity to rapidly arrive at answers for agricultural problems, such as how to deal with insect pests or boost the nutritional profile of a crop to promote health benefits. By using the genetic capabilities held within seeds, farmers have the opportunity to solve some problems at crop level.

GM crops and Australia

The first commercially available transgenic food plant – with its genetic make-up manipulated through modern biotechnology rather than traditional breeding – was the 'Flavr Savr' tomato, initially approved for use in 1994 by the US Food and Drug Administration. This tomato plant's genetic modification allows the ripening of its fruit to be to be delayed after picking, extending the fruit's shelf life, allowing it to be transported over longer distances and timeframes without spoiling.

In 1996, the US-based multinational agrochemical and agricultural company Monsanto entered into a partnership with Australia's national science agency CSIRO which led to the first Bt cotton crop grown in Australia. Bt cotton has an inbuilt natural insecticide, which was originally found in a bacterium (the name 'Bt' comes from this bacterium, *Bacillus thuringiensis*). The use of this cotton variety has since helped reduce pesticide use significantly on Australian cotton crops, contributing to an 80% reduction in insecticide use by the industry this century.

In Australia, canola oil derived from genetically modified crops is used in spreads, tinned food and for deep frying but there are currently no GM fresh foods, such as fruit and vegetables, grown in Australia. We do however allow manufacturers to use imported GM food ingredients in products such as soybeans, canola, corn, rice, sugarbeet, potatoes and cotton.

Measuring economic benefits

The potential disruptive impacts of new technologies can at times be overestimated. One can find literature that both supports and refutes the economic benefits of genetically engineered crops to farmers. Economic benefits have been shown to depend on context, including the type of crop grown, the variety, location and farming practices. Results differ widely from country to country, mostly due to well established farming practices. GM canola and cotton grown in Australia do not generally show higher yield from using the technology. The primary benefit to

Australian farmers is derived from lower costs of production, i.e. easier weed control, less tillage and a shorter production cycle.

Assessing health and safety

Some opponents to genetic modification question the potential effect on human health of eating the products of GM crops, fearing that allergic responses could be triggered by the insertion of genetic material from plant or animal products – such as peanuts, eggs and wheat. And there is concern the change in genetic make-up that results from introducing GM insect-resistance might add toxic properties to food or reduce its nutritional value.

Research to date shows that concerns about both allergens and toxins are unwarranted. It confirms that genetic modification has not introduced any new or altered hazards into the food supply. And it shows that the potential for long-term risks associated with GM foods are no different to those associated with conventional foods.

There is also concern about potential environmental impacts of the technology e.g. emergence of 'superweeds'. Crops can cross breed with other 'wild', plants whether they've been produced by biotechnology or through traditional breeding. Research shows cross-breeding is no more likely to occur for GM crops. In both cases, preventing the unwanted transfer of genes between wild and crop plants depends on good farm management practices.

After a quarter of a century of research into the potential health issues, the European Commission reported in 2012 that '[There is] no scientific evidence associating GMOs with higher risks for the environment or for food and feed safety than conventional plants and organisms' [338]. Food Standards Australia New Zealand has arrived at similar conclusions based on their own studies.

Judging risk in new technology

If studies show GM crops increase crop yield and decrease crop production costs for farmers, why is there public aversion to the use of these plants? Some of the resistance to the technology is complex and contradictory. For example, some opponents of GM crops claim the crops are bad because they are 'unnatural'. But the meaning of 'natural' plant breeding is blurred because all commercial approaches involve some form of genetic modification. For example, heat, chemical and radiation techniques are used to alter the genetic composition of plants in 'conventional' breeding. This appeal to nature fallacy is referred to as a cognitive bias. Such biases are decision making tools employed to make decisions. When people are faced with uncertainty or lack of comprehensive information they will look for ways to make sense of unexpected and unknown events, and use these mental shortcuts to judge risk.

Language, labels and categories also play a crucial role in the perception of risk. Those opposed to GM crops have been able to exploit powerful language to influence how consumers will interpret and understand food derived from biotechnology e.g. use of the word 'Frankenfoods' has been used to invoke fear into the consumer.

Regulation

There is no evidence to date to support the claim that there is a difference between crops produced by conventional plant breeding or genetic modification techniques. However the level of scrutiny and regulatory compliance burden applied to GM crops does not apply to traditional breeding techniques that are similarly unpredictable in the products they produce.

One of the consequences of this heavy regulation is the market dominance of a few financially powerful companies for GM products. This is particularly notable in the case of genetically modified Golden Rice. This genetically engineered crop was developed by a public institute for a humanitarian project to address significant Vitamin A deficiency in poor countries. The lengthy and expensive testing and regulatory regime for GM crops and the risk that consumers will reject the products, means that only a handful of large companies can afford the risk of developing them. The cost for the development of a GM variety is currently so great that it is difficult for a public institution or small to medium enterprise to enter the market.

How values and beliefs inform attitudes

Science and technology cannot be considered in isolation from values; many emerging technologies trigger debate about ethical, legal and social implications from invention to use. For instance, the attitude people have toward corporate monopolies has been shown to influence their attitude to genetically modified crops. A person's perception of risk does reflect and reinforce their worldview.

In the mid-1990s, the movement against genetic engineering gathered strength in some European countries. It was exacerbated in 1996 when Monsanto introduced GM soy into Europe and did it without transparency about the origins of the product. People were (rightly) outraged and jumped on this lack of disclosure as proof of the power and manipulation of companies in the GM industry.

Resistance to the technology and its products has been in part attributed to a fundamental mistrust of such large corporations. In some cases, scientific evidence supporting the safety of GM crops is dismissed on the basis that scientists cannot remain commercially impartial, given the influence of big business. Despite the potential, regulatory approval has delayed the deployment of Golden Rice to people in need for over ten years.

Conclusion

In addition to improving agricultural practices, reducing waste and improving nutrition, GM crops have the potential to address food security issues by increasing crop yield and improving food quality and nutrient composition. The history of agricultural practices shows that the ability to modify, create and select crop varieties is not new but yet there remains some strong opposition to its use. The way in which genetically modified crops are understood, categorised and explained do effect how they are perceived and ultimately regulated.

Public uncertainty about GM crops is heavily influenced by the fear of the new and unknown. In many ways it reflects similar community responses seen in the early days of many new food technologies such as refrigeration, canning and pasteurisation. When it comes to making food choices, studies have shown that consumers value taste, 'naturalness', convenience, healthiness and price. Four of the five leading beneficial attributes for organic foods revolve around what it does *not* contain, such as the use of toxic chemicals and preservatives. Addressing these preferences in an open and transparent way could be one important solution to marketing GM products to consumers.

Wider objections to GM foods are often based on concerns about human and ecosystem health, consumer choice and fairness, fear of unintended consequences and economic issues. The level of regulatory burden on GM crops is not currently supported by any proven harm or risk. Regulation of GM crops must be based on an evidence-based approach so that all nations are able to benefit from the technology. It is crucial the safety and efficacy of the products of genetic engineering are assessed and regulated, not the technology itself.

Under current regulatory conditions, the reality is that the sort of financial investment needed to support the substantial research and development that underpins GM crops has led to a greater monopoly discouraging smaller biotech companies and publicly funded organisations from pursuing the technology.

Full working paper available at http://acola.org.au/index.php/new-technologies-contributing-reports.

C.5. Locked into the car

Overview

- The internal combustion engine is a defining technology of the 20th century that has completely changed modern landscapes and mass transport.
- This transformation was brought about by incremental changes in technology and on business models based on mass production, low costs and highly effective marketing.
- Access to cheap, private transport has increased individual freedom and rural access. The car has changed the shape of urban development and brought congestion, accidents, a faster pace of life, stress and a rise in sedentary lifestyle.
- Society is locked into a host of secondary technologies that support the use of cars, such as tarmac roads, car parks, garages, fuel stations, traffic lights, fuel distribution networks, motorways and flyovers.
- This technological lock-in could be changed by a host of factors in coming years: petrol shortages, taxes to control carbon emissions, developments in alternative technologies and components. The impact of any change could be considerable.
- There has been more than 100 years of research and development into internal combustion. Nevertheless, engines still suffer from significant problems of fuel efficiency, an inherent problem with machines based on internal combustion.
- Analysis of alternatives to conventional petrol-powered vehicles, such as the hybrid car, which uses electric power and petrol, shows no marked difference at present in overall environmental benefit because the generation of electricity (from fossil fuels) is currently the main source of electrical power.

Introduction

The petrol-powered car produced major changes in society throughout the last century. Thanks to the car, we enjoy freedoms unimagined by our 19th century predecessors. We can make long distance journeys at our convenience and access jobs and services that were previously unavailable. The car has helped liberate millions of people. At the same time, huge numbers of individuals die in traffic accidents (1.24 million a year worldwide according to the World Health Organisation), while problems of congestion, traffic jams, stress, air pollution and environmental damage affect everyday life. None of these impacts were anticipated a hundred years ago.

Today the car has become integral to modern life, but it is not immune to future change. Oil supplies may one day dry up, if advances in oil exploration technology fail to keep up with demand, while carbon levels in the atmosphere could rise so dangerously that we may have to turn to other types of transport. Learning from the past, specifically from cradle to grave evaluations, considerable care will have to be taken when we cost these alternatives and assess the continued use of the car. The ubiquitous use of vehicles is embedded in our way of life. We have come to love this technology and it will be hard to move beyond it.

From the horse and buggy to the Model T

The petrol-powered car was not invented in response to grave necessity. There was no transport crisis at the end of the 19th century. Most citizens were quite content to use bicycles and horse-drawn buggies. Automobiles were initially bought by the rich as toys, and were only sold to 'suitable' customers.

By contrast, manufacturers of petrol-powered cars aimed their vehicles directly at mass markets, and by using assembly line techniques and the mass manufacture of interchangeable parts, drove costs down dramatically. In doing so, they made purchasing cars, and the freedom this brought, a reality for a large part of the population. The Model T Ford quickly replaced the horse and buggy in the USA and Australia as a practical and economical mode of transport.

The 'Ladder of Success'

Powerful marketing, developed in the USA, also played a key part in making the car an item of status. The automobile became a visual representation of an owner's success, and consumers were urged to move up the product ladder from Chevrolet to Pontiac, Oldsmobile, Buick and Cadillac. This was known as the 'Ladder of Success'. An expensive car was equated with a positive self-image. In addition, annual style changes and planned obsolescence by companies such as General Motors ensured car sales were kept to a maximum.

Unintended consequences

The car's rising popularity produced some unintended benefits, particularly when it came to public health issues in cities. In 1880, New York and Brooklyn had a combined population of 150,000–175,000 horses. Each horse produced between 15–30 pounds (6–13.6 kg) of manure and a quart of urine a day. Thus, 3–4 million pounds (~1350–1800 metric tons) of manure and 40,000 gallons (150,000 litres) of urine were deposited daily on city streets and in stables. Vacant lots were piled to heights of 18 m with manure on which billions of flies bred, spreading diseases such as tetanus and typhoid. These health problems were an unintended consequence of horse-drawn transport, and they disappeared with the spread of the motorcar; however, automobiles brought their own problems.

Technological lock-in

The car produced a major shift in society, providing owners with increased freedom and opportunities for recreation. For the first time, individuals could move considerable distances whenever they wanted. Travelling further also made it easier to find jobs, while deliveries and other service industries became much more accessible. The rise of the car also required the creation of a pervasive infrastructure of networked roads, bridges and footpaths, as well as garages, service stations and fuel distribution. Driving cars has also had a considerable effect on the pace of everyday life. We expect to cover great distances at high speed. This has introduced urgency and stress to modern life, while congestion, which thwarts the ability to travel quickly, has induced effects such as road rage.

Counting the costs

More than one million cars were sold in Australia in 2012. The industry had a total turnover of $160 billion, included more than 110,000 businesses, employed more than 313,000 people and was the largest contributor to manufacturing R&D in the country – investing about $694 million in 2010–2011.

Conversely, the annual cost of road crashes in Australia is estimated at $27 billion a year while the social impacts are devastating. In addition, the gross economic burden posed by transport pollution to Australia's capital cities was estimated in 2000 as being at around $3.3 billion a year, while the number of deaths caused by traffic pollution that same year was calculated as being slightly higher than the number of traffic fatalities. For example, it was estimated that the number of deaths from pollution in Australian capital cities ranged between 758 and 1703 while deaths from road fatalities in these cities totalled 740.

These widely disparate costs and benefits to society show that when assessing the value of any technology, a narrow view is almost always misleading.

Reaching the limit

Car companies and governments have spent vast sums trying to improve the performance of cars over the past century. For example, in 2011–2012 the Australian Automotive Industry's R&D budget reached almost $700 million. Such investments over the years have produced dramatic changes in the shape and performance of the car. Compare a Ford Model T with a modern Ford Focus, for example. The laws of thermodynamics impose a ceiling on continued improvements, and even today the internal combustion engine has serious problems with efficiency. It is inefficient in converting petrol's chemical energy into mechanical power and loses energy to friction and heat. According to the California Energy Commission, only 15% of the energy put into powering a car engine is used to move the car, and the rest is lost through heat and noise. By contrast, when a car's air conditioning is used in a hot country, it can account for up to 30% of fuel consumption.

Doing it alone

The average car weighs more than 1000 kg. Its driver is usually less than 100 kg in weight. Thus, a car with a single occupant is using most of its fuel to move the vehicle – not the individual. Replacing steel car parts with plastic and composites, such as carbon fibre polymers, improves fuel efficiency by reducing vehicle weight. But the high cost of recycling and disposing of plastics and composite materials, compared to steel, means that a car would have to be driven for more than 132,000 km in its lifetime before any improvement in overall fuel costs could be achieved.

It would wrong to conclude from this data that work on producing lightweight cars should not be pursued because technological developments are likely to decrease the cost of production and disposal processes. The goal remains worthy. It is clear that care will have to be taken to include costs of production and disposal processes when designing lightweight cars for the future.

Stopping the petrol guzzler

Attempts to reduce the fuel consumption of cars are also bedevilled by legal problems. For example, in the USA laws were introduced so that any car with a consumption that exceeds a particular threshold will incur increased taxes. The law does not apply to trucks, a category of transport to which the sport utility vehicle (SUV) belongs. Sales of these large station wagons, with four-wheel drives, soared in the wake of the new law. Thus, a bid to encourage fuel efficiency in cars backfired and instead encouraged the purchase of fuel inefficient vehicles. The complex nature of society can make it very difficult to predict the future adoption of technological innovations.

Taking a different route

Many alternatives to the internal combustion engine are now being developed. They include electric cars, hydrogen fuel cell vehicles and hybrid cars that use electric engines when travelling at low speeds and petrol engines when moving faster. Of these, the hybrid car is the most popular. According to 2012 figures, about 60,000 have been sold in Australia. Many improvements still need to be made to these vehicles to encourage mass adoption. For example, the development of batteries with five times the storage capacity of those currently available could significantly increase the demand and therefore the sales of electric cars.

One idea to bring about these improvements is to copy the concept of car races, such as the Indianapolis 500 and Formula One. These races have acted as motivators to push through improvements in performance of the internal combustion engine. The electric equivalent, known as Formula E, is now being promoted with backers including Hollywood actor Leonardo DiCaprio.

It's a gas

Cars that use hydrogen fuel cells to generate power are also rated as contenders to create zero-emission vehicles. Their engines are significantly more efficient than the internal combustion engine and emit no carbon dioxide. But the current method of producing hydrogen (from natural gas) means that for every mile travelled by a car that is powered by hydrogen fuel cells, the equivalent of 175gm of carbon dioxide is produced. By contrast, a Volkswagon diesel produces 145gm of carbon dioxide over the same distance, while a Toyota Prius generates 167gm over the same distance. Significant reductions in the carbon emitted during hydrogen production therefore need to be achieved before fuel cell cars can reach zero emission status.

Conclusion: Facing the future

There have been more than 100 years of research and development into the internal combustion engine, yet its fuel efficiency remains limited at between 10–20% and the demand remains almost unabated. Nevertheless, the future of the car industry would seem to be one that is still dominated by petrol engines. Most suppliers and manufacturers are happy with the status quo and most drivers and owners of cars have strong emotional links with their vehicles.

An awareness of the harmful environmental effects of the internal combustion engine has only become available in the last few decades - long after the car had become so deeply integrated in everyday life. An attitude of adaptation to new technologies needs to be fostered for any significant change in personal transport to occur. Hybrid cars, which use both electricity and petrol for power, are likely to be pursued vigorously within the industry. Electric cars – created in the wake of improvements in battery technology – remain a secondary option.

Full working paper available at http://acola.org.au/index.php/new-technologies-contributing-reports

C.6. From Frankenstein to the Roomba: the changing nature and socio-cultural meanings of robots and automation

Overview

- Historically, automation innovation in the West is perceived to be shaped by a fear of technology replacing humans in their jobs.
- Reports from countries around the world indicate that as robot productivity increases, unemployment decreases. However, there is a need to invest in human skills to take advantage of the promise of automation technology.
- Improvements in technological sophistication of devices mean that robotics and automation are evolving to reach new domestic markets, including home cleaning, health care, and home entertainment.
- There is considerable cultural difference in forms of robotics innovation. In the US, the prime concern focuses on space and defence devices. Japan and Korea is most interested in robots to help with health care while Europe is concerned more with urban transport.
- Australia has developed a strong industry for manufacturing and using robots in mining and cargo handling.

Introduction

Robots are already employed in industry to carry out precise, highly repetitive tasks – for example in car assembly lines – or in places that are perilous to human beings, such as mines and nuclear power plants. But now their role is expanding. As industry moves away from mass manufacture and turns to making goods that are more specifically designed for individuals, robots are used to help tailor products to specific needs and demands. Critically examining the different design and use of robots around the world reveals new emerging markets and opportunities. In Japan and Korea, for instance, automated devices are being designed to help the growing numbers of elderly people. Also, the size of a nation is less likely to affect the development of a robotics industry. Relatively small nations – like Sweden and Italy – are creating significant industries in the field.

Fear of automation

A brief glimpse into automation's origins, promise and threats provides insight into how it continues to be imbued and influenced by a range of socio-technical actors, which shape how we tell stories about, invent and use automation/robots in our everyday lives. Although two centuries old, the legacy of luddism remains relevant to understanding many enduring attitudes towards automation and robots. The term 'luddite' comes from an historical account of a group of early 19th century workers who protested against the introduction of automated devices to replace human-operated weaving machines. Fearful of the loss of jobs, they broke into factories and destroyed these new technologies. We see contemporary manifestations of this fear. In the West, robots feature most significantly in popular culture as threatening technological forces. Although framed as 'entertainment' these communication mediums are nevertheless critical in shaping people's perceptions about technologies. The *Terminator* films provide vivid examples.

For many, negative perceptions of robots are fundamentally associated with the loss of jobs and fears about agency. Dmitry Grishin, founder of Grishin Robotics, stresses the importance of this point. 'If people don't know what a device is doing they call it a robot,' he states. 'Once the device start to do something useful, they are not called robots. They are called vacuum cleaner, car, aeroplane, coffee machine. And a lot of the stuff that we use today on a regular basis, 20 years ago people called a robot.'

Beyond the assembly line

The rise of automation is generally traced to the days of Henry Ford in the early 20th century when his car assembly lines first provided Americans with affordable automobiles – with little variation. The 1970s heralded the arrival of a new approach – post-Fordism – in which the needs of individual consumers became the focus of attention. Goods and services were increasingly designed to reflect individual tastes, habits and preferences. Robots, once the prime concern in manufacturing industries for the purpose of large-scale assembly line production are increasingly being put to use in more intimate, personalised contexts such as the care of the elderly and home entertainment.

Robots in Australia

In Australia, robots were first used in the manufacturing industry in the 1970s. A decade later, they expanded into farming with the first sheep-shearing robots appearing in 1980. At this time, robots – which were all imported to Australia – were used to carry out monotonous, repetitious tasks. The main inhibitors to growth in this sector at this time were attributed to the lack of skills to run and manage them. The public also remained unconvinced of their value. A poll, carried out by the Australian Science and Technology Council in 1996, found that almost 60% of young Australians thought that computers and robots were taking over jobs and increasing unemployment. One third thought computers and machines would eventually take over the world.

Yet, sales of robots have continued to rise due to a combination of factors: decreasing prices of machinery, improved miniaturisation, economic growth and more sophisticated robot designs. In the last decade, improvements in sensor technology – which have allowed robots to carry out far more sensitive tasks than they had in previous decades – has led to a surge in sales in industrial robots. For example, more than 100,000 new robots were installed in Asia/Australia in 2013, an increase of 18% from 2012.

Home alone

Robotics and automation have evolved so they are reaching new, smaller targeted consumer markets. This is due to reductions in size and costs of manufacture coupled with increased technological sophistication. According to the Robotics Industries Association (2013), this application of robotic technology is less focussed on mass manufacturing and more concentrated on producing customised products.

As a result of this shift, robots are beginning to make an impact in domestic and personal services such as home cleaning, health care, and home entertainment. At the same time, the global market for service robots for professional use is also growing. The International Federation of Robotics forecasts the value of this market from 2014–2017 to be worth US$18.9 billion and will include robots for defence applications, self-guided vehicles, maintenance and cleaning, medical robots, public relations robots (for museums and supermarkets), construction and demolition, and surveillance and security.

In Korea and Japan, the increase in the robot market will be most noticeable in the service categories where they will act as aids for caring for the sick and elderly, reflecting the needs of these countries' growing ageing populations. An example is provided by PARO, a furry robot baby seal, made in Japan, that can replicate emotions such as surprise, happiness and anger and which is designed to have a calming effect on hospitalised elderly patients, including individuals suffering from dementia. The growth of this market can also be related to differences in cultural understandings about the use and applications of robots. In some Asian countries, as cultural anthropologist Dr Genevieve Bell of Intel Corporation has argued, robots have been far less maligned with violent personality traits.

Robots around the world

Strength and size are not critical features for success in the global robot market. In his 2008 book, *Robotics: State of the Art and Future Challenges*, George Bekey surveys the robotics markets of Japan, Korea, US, France, Germany, Italy, Spain, Switzerland, UK and Australia, and outlines major differences between them:

- The US leads the world in space and defence robotics.
- Japan and Korea dominate in the areas of care and personal robots, including those involved in entertainment.
- The European Union has many programs focusing on urban transport as well as elderly and home care.
- Australia is dominant in robots involved in mining and cargo handling.

Bekey stresses that a culture of experimentation, interdisciplinary collaboration and financial support is critical to achieving success in the field of robotics. However, the size of a country is not the key driving force. Indeed, relatively small nations – for example, Sweden, Italy and Japan – have significant presences in the field. Indeed, there are more start-ups in Europe than in the US, despite the latter's entrepreneurial reputation. In addition, Europe, Korea and Japan had more networks and robotic organisations, although Bekey failed to note any at the time of writing in 2008.

In the US, the prime driver for robotics comes from military programs and US Department of Defense research. In Europe, Japan and Korea, the drivers are social and economic with Asians having, in particular, identified the potential key role that robots can play in an ageing society.

The human touch

An important aspect of building sociable robots is the benefit that will be gained in the process from improving our knowledge of social intelligence and human sociality, a point stressed by Cynthia Breazeal of the Massachusetts Institute of Technology notes in her book *Designing Sociable Robots*. 'It is important to consider the specific ways in which we understand and interact with the social world. If done well, humans will be able to engage the robot by utilising their natural social machinery instead of having to overly and artificially adapt their way of interaction.'

As the use of robots expands and they play increasingly important roles in our lives, new issues will have to be considered. In the West, there is a general aversion to robots looking too human, which is not shared with citizens of other countries. On the other hand, some comfort can be taken from the issue raised by Grishin: a robot that carries out a recognisable task and is embedded in everyday life – such as a coffee maker – may eventually be seen in a less sinister light and accepted as being harmless by users.

Another example is provided in driverless cars. Google is developing such a vehicle, which would be driven by automated machinery, and four states in the US have already passed laws permitting driverless cars. They offer several benefits: they are likely to cause fewer accidents, apparently will not be affected by or trigger road rage and will have better fuel efficiency. However, it is critical to remember that these are not neutral technologies. The algorithms built into the computing are not universal, or placeless, rather they come from humans who are socially, culturally and historically shaped, and as a result the technology needs to be examined for the inherent complications already built into the design. In addition, revision of current legislation is required to accommodate and negotiate shifts in responsibility when crashes occur.

Tentative conclusions

- Global robotic markets are shifting towards smaller, targeted and customer models.

- While industry and manufacturing remains core to many robot and automation companies, focus is now spreading to consumer, healthcare and domestic devices.
- Developments in miniaturisation and sensor technology will support the growth of sociable robots that engage and have relationships with humans.
- Strength and size of markets are not the driving force in modern robotics. Small countries can do well. However, a clear national program, with government support is needed to drive innovation.
- It is critically important to educate the general public about the importance of technology to avoid luddism (the fear of machines taking jobs).
- Australia responded quickly and successfully to the emergence of automation in the 1980s and has been dominant in large-scale applications, such as mining and cargo handling.
- Training is critical to develop an understanding of science and technology that underpins innovation. To take most advantage of technological change, it is essential to invest in human skills, not just in equipment. This should start in schools, not just in tertiary education.

Full working paper available at http://acola.org.au/index.php/new-technologies-contributing-reports

C.7. Technology and work

Overview

- New technology both creates and destroys jobs. On an aggregate level, the net number of jobs created is positive; but at the level of the individual, technological unemployment can and does occur.
- Changes in technology adoption in the workplace can take time to flow through, but then trigger sudden bursts in adoption and dramatic shifts in the workforce.
- Predicting which technologies will impact on work is problematic, as adoption depends on usefulness, cost, worker acceptance, uptake and market forces; however, methods – based on identifying problems and potential solutions – are useful.
- Information and communication technologies are one of a number of 'general purpose technologies'; applicable across all industries, these technologies are adopted at different rates but their effect is pervasive and profound, disrupting existing structures and affecting an entire economy.
- Countries and companies that adopt and deploy innovation fare best.
- Education and training that focuses on problem-based learning and critical thinking, as opposed to tradition-bound and standardised curriculums, are more likely to engender worker adaptability, faster adoption of new technologies and employment growth.
- Understanding any technology change (relevant to work or otherwise) requires accurate comparison: evaluation at aggregate levels will give one conclusion whilst evaluation at the individual level will give another conclusion. One cannot infer population wide conclusions as relevant to every individual, and vice versa.

Introduction

Technology, like a double-edged sword, cuts both ways: it creates jobs, and destroys them. It empowers people, expanding their capability to achieve tasks, but also makes some tasks redundant. The history of technology in the workplace since the Industrial Revolution shows that while job categories can shrink dramatically or entirely disappear, new job categories materialise – often as a result of the technologies introduced. The remarkable thing is that, despite more than 200 years of this process of 'creative destruction', we have never run out of jobs. The question is, will this continue into the future? And how do we adapt?

The march of progress

History shows that trying to stem the tide of technological change is futile: there are too many incentives at play. If a new technology arrives and a company ignores it, it does so at its peril.

Take Kodak, the leviathan of photography, born from innovation: its founder, George Eastman, did not invent the camera or the photographic process but he simplified it with film in rolls and mass-produced boxed cameras, outsmarting rivals and marketing his products in novel ways. Yet by 2012, it declared bankruptcy (Kodak has since reinvented itself as a as a commercial-printing company, and is out of bankruptcy). Ironically, Kodak initially pioneered digital cameras, but was slow to take advantage of that lead and remained focussed on film. Having failed to adapt quickly, Kodak suffered as the market for film disintegrated – slowly at first, then dramatically. Having a 'Kodak Moment' used to be a marketing slogan the company used to sell film; now it's used to describe a tipping point where a company fails to innovate fast enough as it fears the impact such innovation will have on its primary markets – and suffers catastrophically as a direct result.

Tech in the workplace

Technology is adopted in workplaces for a number of reasons: greater efficiency, improved profitability, competitive pressure, worker safety and convenience, consumer demand, brand perception (appearing 'up-to-date' or 'future-focussed') and regulation.

Nevertheless, there are barriers to new technologies: workers are less willing to accept those that are unfamiliar, or perceived as being a threat to their jobs or conditions. For example, mobile phones and GPS navigation may boost the efficiency of truck drivers, but also make them available at all hours and record their movements; nevertheless, as both technologies are in common usage, these are more likely to be accepted. GPS trackers that log times and stops made – a feature useful for fleet management and customer delivery timing – will, however, likely be seen as infringing on a driver's autonomy and make them feel monitored and accountable for how work hours are used compared with other drivers.

The adoption of some technological advances are driven by workers, such as the 'bring your own device' phenomenon, where staff use their own smartphones, laptops and tablets for access and use of corporate networks.

Forecasting the future

Predicting which technologies will be adopted *en masse* in future is a fool's errand: research repeatedly shows that such efforts have a 50/50 chance of success – as good as flipping a coin.

There are three main factors at play in technology adoption: feasibility, social impact and cost (and hence potential market). Just because something is feasible, does not mean it will be used – take videophones, technically available since the 1970s but too expensive to make and seen as too intrusive. Yet today, many people make video calls on computers and tablets every day, as technological costs have fallen and the video component is in control of the recipient as well as the caller.

A more successful method for prediction is to identify problems in society and industry for which various technologies exist, rather than the particular technology that might be used. Sociologist S. C. Gilfillan in a 1937 report to the then U.S. president correctly predicted that landing airplanes in fog would become commonplace – but not which of the 25 technologies being examined would do this. By 1941, a radio beam transmitter technique known as ILS (Instrument Landing System) was in use at six locations in the country, and by 1964 automated landings using ILS came into use.

Learning from evolution[128]

Evolutionary theories of technology represent an alternative approach to understanding technological change. Drawing upon theories of evolutionary biology the analysis of technological change shows the formation of emerging technologies as the creative combinations of gradual improvements in technologies (e.g. transistors, graphical user interfaces etc.) resulting in specific applications (e.g. personal computers). These gradual improvements generally occurred over long periods of time but it is the pervasive use of a technology application that increases the visibility and measurability of a technology application (e.g. the economic impact of ICT). This approach can be useful in understanding the impact of 'disruptive technologies', such as personal computers and the internet: slow at first, but eventually powerful and far reaching.

Identifying which technologies will be disruptive can be difficult: again, feasibility, social impact and price are factors. Google's driverless cars may appeal to transport companies, but LIDAR – a remote sensing technology needed to measure distance by bouncing lasers off objects and generating a detailed 3D map of its surroundings – currently costs upwards of US$25,000 apiece. Nevertheless, the artificial intelligence software developed for the project makes driverless vehicles possible, and if LIDAR can be made more affordable – or another, much

[128] See Chapter 2: How technology changes for a thorough discussion of technology evolution, revolution and disruption

cheaper remote sensing technology developed – there would be enormous ripple effects on the future workforce by decreasing the need for manned vehicles: there are almost 340,000 drivers in Australia working in road transport, postal and courier services.

The ICT revolution

Computers, digitisation and the internet – commonly known as information and communication technologies (ICT) – are considered a special form of technological advance. It is a general purpose technology, widely applicable across industries and walks of life and capable of drastically altering pre-existing economic and social structures. Other examples of general purpose technologies include electricity infrastructure and the automobile.

Technological *revolution* rarely arises without a period of technological *evolution*: the revolutionary nature of a technology is often only fully appreciated with the benefit of hindsight, after many gradual changes occur and build toward a radical overhaul of the existing order. Take the automobile, which not only transformed transport in the 20th century but radically altered the design of cities and whole economies. It required the development of the internal-combustion engine, which evolved slowly as a concept after the first turbine was patented in Britain in 1791. Engineers and physicists tinkered with combinations and designs using various chemical fuels (such as hydrogen, gas, peanut oil) as well as electric batteries before Belgian Étienne Lenoir produced a gas-fired engine with cylinders, pistons, connecting rods and flywheel in 1849; even then, his design was similar in appearance to a horizontal double-acting steam engine, in which gas essentially took the place of steam. It took until 1884 for the first of what we would today recognise as an early petrol engine (with a spark plug, ignition magneto, coil ignition and carburettor) to be developed, followed by decades of technological and design evolution before the mass-produced automobile with an enclosed cabin, brakes and a steering wheel went on to revolutionise society.

Truly a revolution?

It’s useful to compare the impact of general purpose technology such as electricity infrastructure with ICT, which shares many of the characteristics: widespread application, requiring a fundamental reorganisation of infrastructure and labour, and demand for higher skills and a lag time between the technology’s arrival and its ultimate impact.

Measuring electricity infrastructure in terms of households obtaining an electric service (from 1894) and the availability of the first personal computer (1971) shows households adopted electricity approximately as rapidly as they adopted the PC.

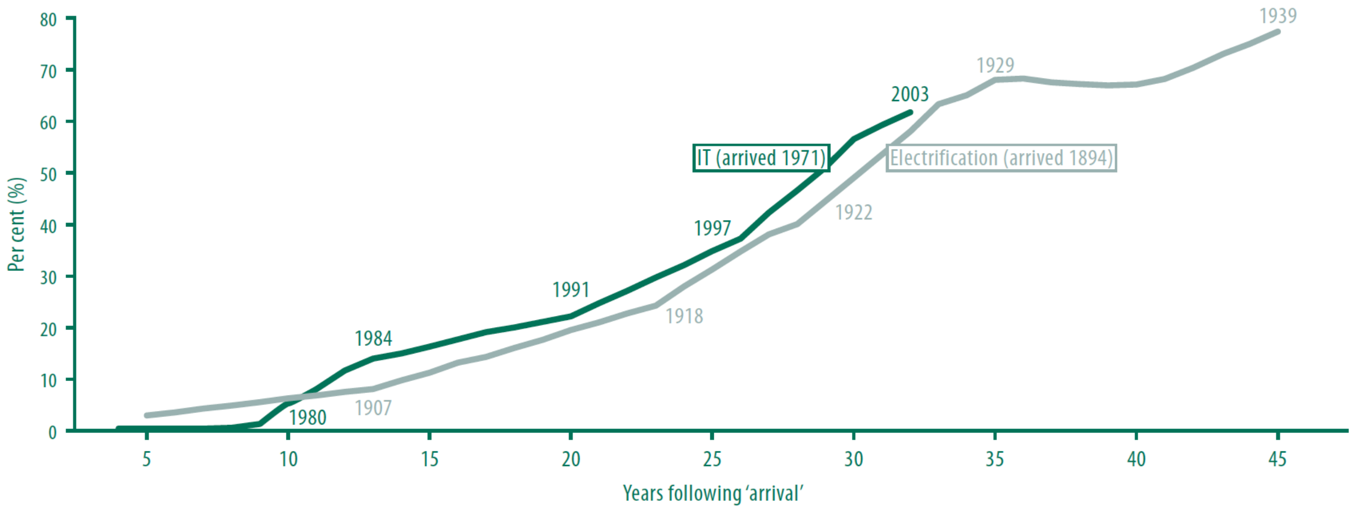


Figure WP1. Percent of households with electric service and PCs during the two general purpose technologies eras. Sourced from [539].

Only 10% of manufacturing 'horsepower' was derived from electricity in 1905, but by 1925 this had jumped to 70%. Adaptation and large employee turnover were hallmarks of the American workforce in the first decades of the 20th century – during this time of mass adoption of electricity, most U.S industries (meat-packing plants, textile mills, machine works and automobile factories) had a labour turnover of 100%.

The use of electricity brought opportunities and challenges to the workforce of the early 20th century, just as ICT does now. It allowed managers to maximise economies of scale by building large, continuous pace manufacturing plants, and the move from mechanical to electrified plants created a safer, quieter, cleaner and brighter workplace. By contrast, on an individual employee level, new risks included electric shocks or electrocution, generally for the young or newly employed. Attitudes to electrification at the time were negative as textile workers felt they were expected to complete ever-increasing amounts of work and there are documented reports of workers experiencing nightmares about keeping up. This is comparable with modern concerns among employees that mobile communications and email is expanding work hours well outside of the working day.

Electrification also led to new management practices as better-educated engineers became responsible for managing work processes in factories, which in turn led to the re-design of production. This also created new incentives for management to seek an accommodation with workers over pay and conditions, as mass production relied on a long-term, reliable labour supply with a modicum of skills (making cheaper – but high-turnover labour – less profitable).

In the same way, ICT has also changed middle management, whose oversight, planning, budgeting and analysis of production, costs and sales rely on a host of technologies and processes which themselves require highly skilled staff. Increasingly, their employees also require ICT skills to operate machinery, manage sales and inventory and track transactions.

Technology and employment

Historians have noted that before they improve productivity, general purpose technologies may actually decrease it, due to the cost of replacing older technologies and skills, the need for worker retraining, and time for the development of new systems and infrastructure to cope. Once general purpose technologies become mass adopted, however, they boost productivity – but also destroy jobs as they in turn create new ones.

Employment turnover is a normal feature of the broader economy. Every year, jobs are destroyed by companies going out of business or downsizing, while new companies are born and others expand. The number of new jobs 'created' is really the net number of jobs added less those lost. For example, 15.7 million jobs were created in the U.S. in 2011, but net job creation was only 2.6 million because 13.1 million jobs were also destroyed. It's estimated that, on average, 15% of jobs are newly created every year in developed countries. Thus, when we talk about technology destroying jobs, what we are really talking about is technology increasing the rate of job destruction compared to the rate of job creation.

At an individual level, the fact that new technologies create jobs does not make workers any less anxious about their particular job. While most workers who lose their jobs from technological change may take time to find new jobs, some may drop out of the workforce altogether. This, it should be noted, is also a feature of normal employment turnover.

The rise of robots

One of the most hotly debated topics in the impact of technology on the workplace is that automation, artificial intelligence and robots will lead to a major structural change in the economy and widespread unemployment. Historians note that throughout the 20th century, recessions and periods of high unemployment have been repeatedly attributed to technology and automation; however, so have economic booms.

Some scholars argue that the current pace of change in automation is increasing, and pushing into areas long believed beyond the scope of computers. In their recent book, *Race Against the Machine*, Erik Brynjolfsson and Andrew McAfee of the Massachusetts Institute of Technology argue that the trend will only accelerate. Today's rapid advances in natural language processing, artificial speech, vision and learning, and the proliferation of fast and inexpensive computing devices – coupled with access to vast amounts of data (which can be more easily interpreted by computers and robots) – is making it possible for automation to reach into wholly new areas.

However, these capabilities did not come about overnight or even over a decade. The introduction of ICT dates back to at least 1946, when the first programmable computer was developed. It took two decades of technological evolution before mainframe computers became a fixture in large organisations like banks and government departments, and another two decades – following the arrival of desktop computers – for ICT to enter widespread use in industry, business and among consumers. Both required evolutionary changes to increase speed, versatility and bring down cost in order to make them possible. They in turn led to the evolution of computer networking from its limited use by the military and academia in the 1970s, to what we know today as the internet – which by the 1990s had spawned multiple new industries and triggered job growth, as well as job destruction.

It's true that as a result of the widespread proliferation of ICT today, and the drastic fall in the cost of processing power, computers can now begin to tackle problems – like real-time 3D sensing – that, until recently, only people could handle. But it's worth noting that a photocopier can also be considered a robot, and its appearance did not lead to the disappearance of office workers who once made mimeographs and Gestetner (spirit duplicator) copies, but rather their redeployment to other functions.

Automation and increased employment

Much the same may happen with the new wave of 'collaborative robots' – which can work safely alongside humans and interact with them. An example is Baxter, made by Rethink Robotics in the U.S., which comes embedded with common-sense software, requires no programming, can be shown a task by a human operator and learns on the job – much as people do. Launched in 2012, it costs around US$25,000 and is targeted at small to medium businesses. Another is Denmark's Universal Robots, whose UR-5 and UR-10 look like disembodied arms with cameras attached, and can be operated by desktop controllers and taught tasks using tablet computers. Both robot makers say customers who have purchased their machines to automate tasks have hired more people – rather than let jobs go – following gains in efficiency and output. In 2013, Google, the internet search giant, had acquired eight robotics companies which suggests that robot automation may be approaching more widespread use in industry and society.

While robot automation may transform the workforce and eliminate some jobs, it will also likely create new kinds of jobs. The McKinsey Global Institute reported in 2011 that 2.6 jobs are created for every job lost. Technology-dependent jobs in the information technology sector, the McKinsey report notes, are generally better paid and highly skilled: in the U.S. in 2011, ICT employees earned an average salary of US$78,584 which was 74% more than the average U.S. employee salary of US$45,230.

It is of course possible that the pattern of technological unemployment will be much worse due to automation, artificial intelligence and robots; but it's also possible that because we cannot know for sure, we pessimistically assume the worst, as has often occurred in the past. For its part, the robotics industry takes the opposite view: that the widespread introduction of robots in the workplace will create new jobs – specifically, jobs that would otherwise go offshore to developing countries. In June 2014, the European Union launched the €2.8 billion Partnership for Robotics in Europe initiative, known as SPARC, which it called the world's largest robotics research program and expects will 'create more than 240,000 jobs in Europe'.

R&D and education

Worldwide empirical evidence shows a positive link between a country's research and development (R&D) expenditure, technological innovation and economic growth. Since the late 1970s, the U.S. has snared a disproportionate share of the world's wealth through an aggressive pursuit of technological change. Much of the GDP growth in India and China between 1981 and 2004 can be explained by expanded 'innovation capacity': by linking the science sector with business, establishing incentives for innovation and balancing the import of technology and local R&D, both countries experienced rapid economic growth. All three examples demonstrate that technological innovation is a strong catalyst for economic growth.

Educating to adopt

The importance of education in the ability of a workforce to adapt to technological change has long been recognised; it's been estimated that the cost of adopting to new technologies in the U.S. is around 10-15% of GDP, and scholars believe that education and training plays a role in this, as higher rates of technological change correspond with higher levels of worker training.

In a study for the U.S. National Bureau of Economic Research on the introduction of new technologies into the workforce from 1890 to 2005, Claudia Goldin and Lawrence Katz of Harvard University show there is a 'race between technology and education', leading to economic growth but also wage inequality, since such change favours the more highly skilled and educated workers.

Adapting to technological change requires 'life-long learning' and educational approaches such as 'problem based learning' improve the ability of workers to continue to learn long after graduation.

Conclusion

The adoption of technology into the workplace contributes to employment turnover, the creation and destruction of jobs as well as re-deployment of skills. Technology adoption in the workplace is generally gradual requiring retraining or redeployment of employees.

Focussing on the individuals affected by the adoption of new technology in the workplace (rather the aggregate population of job winners and job losers) is a better way to cope with technological change. However, the gap in income and opportunity between the better skilled and better educated, and those who are less so, is likely to become exacerbated as technological change reaches deeper into the workforce.

What seems to matter more is the degree to which the benefits of technological change are shared or hoarded by the few. There is always choice in the development and adoption of new technologies, and education around technological change are essential to facilitating adoption. Education and training – even from an early age – that focuses on problem-based learning and critical thinking is more likely to create a workforce that is better adaptable to new technologies and more likely to benefit from restructuring caused by technological change.

In addition, the role of governments in making the *benefits* of technological change more evenly distributed (especially during the more disruptive early stages of large-scale change), need to be planned for, and the impact on workers affected need to be considered and catered for alongside the gains being made. As *The Economist* summed up in its editorial of 18 January 2014:

> [T]he benefits of technological progress are unevenly distributed, especially in the early stages of each new wave, and it is up to governments to spread them. In the 19th century it took the threat of revolution to bring about progressive reforms. Today's governments would do well to start making changes needed before their people get angry.

Full working paper available at http://acola.org.au/index.php/new-technologies-contributing-reports

C.8. The education (r)evolution

Overview

- Educational technology is continually evolving.
- Online education platforms have not appeared suddenly; they have resulted from gradual and incremental shifts in social and technological drivers over a long period of time.
- Online education platforms, such as Massive Open Online Courses (MOOCs), can help tertiary level up-skilling and re-training with unlimited participation.
- MOOCs are courses, *not* degree programs, delivered through mainstream universities.
- Online education platforms remove traditional higher education barriers, such as a lack of access, age restrictions and low income.
- Fast-growing nations, such as India and China, are expected to embrace online education as a way of delivering quality education to their burgeoning populations.
- Online tertiary education is underpinning the exploration and innovation of higher education business models and accreditation formats.
- Online education allows Australian universities to attract students from under-serviced markets through the branding of online courses, increasing revenue and creating opportunities through global partnerships, as well as increasing access to student and academic talent.
- Research is now showing that the best education outcomes are achieved through a combination of online and traditional education.

Introduction

Education is always influenced by the technologies of the day. Not long ago photocopiers, fax machines and CD-ROMs directed education delivery. Now the provision of tertiary education involves tablets, smartphones and other lightweight portable computing devices. This equipment, which is becoming widespread in Australia and the rest of the developed world, enables access to the optimal internet bandwidth needed for transferring education course information. And it's delivering a level of portable personal computing power that is making remotely delivered education accessible to a growing student body. One clear outcome has been the emergence and wide uptake of remotely delivered products such as MOOCs (Massive Open Online Courses). The online space is not likely to ever fully replace physically attending a university. But it's clear that online education platforms have become a vital and expanding component of learning.

The rise of online education

Recent worldwide access to online education has not happened suddenly. It's come about through incremental changes in technology and changes in the structure and format of tertiary education over many years.

In Australia, for example, there was a significant shift during the late 20th century in the structure of tertiary education. Apprenticeships declined, and the higher education system changed from three-tiers (TAFEs, institutes of technology and universities) to two, with the merging of institutes of technology and universities in the 1980s and 1990s.

Not surprisingly, Australia – with its huge geographical expanses and many small and physically disconnected population bases – has a long historic connection with remotely delivered education. The Australian School of the Air pioneered education for primary and high school students in remote locations from the early 1950s. A large part of the extraordinary ongoing success of this service has been its willingness to embrace and incorporate new technology; shifting since its inception from pedal to high-frequency radios and now to the current use of two-way broadband satellite networks.

Australia has also embraced the products of Open University, an early provider of tertiary-level distance education. This was first established here in 1993 in a televised format. It's since moved to an online format, and in 2012 it had more than 60,000 Australian student enrolments.

Research reveals why such courses have proved popular. Thousands of studies since the 1990s, both here and overseas, have shown there is no significant difference in learning outcomes between distance and face-to-face instruction; regardless of the discipline, student type or technology medium used.

In terms of technology, the evolution of online education has perhaps been most significantly supported by the spread of lightweight personal computing devices. These have resulted in a significant change in the way students store and access educational materials. They allow, for example, the use of e-texts, which usually cost substantially less than their hard-copy.

The widespread availability of these devices has coincided with rising numbers of students worldwide; increased demand for personalised anytime, anyplace education; and worldwide access to optimal bandwidth high-speed internet.

The MOOCs experience

One outcome of the rise in on-line education is the appearance and rapid spread of MOOCs. These are remotely delivered courses that allow up-skilling and retraining with unlimited participation. And they are becoming widely embraced because they remove traditional higher education barriers such as lack of access, age restrictions and low income. Despite mainstream university involvement, MOOCs are *not* degree programs and are not intended as replacements or alternatives to degrees. However, they would not be possible without the support of reputable universities to provide educational expertise.

From 2011 to 2013 more than 200 universities around the world produced MOOCs, enrolling in excess of 6.5 million students in more than 800 free classes.

The development and spread of enabling technology has certainly underpinned the rise of MOOCs. But there have been other important drivers behind the recent expansion of this form of education delivery. For example, the recent global financial crisis, which decreased employment levels and therefore the capacity to pay for university education in many countries, has helped steer students towards MOOCs because they are either free or low-cost and can be accessed any time.

The rapid and substantial uptake of large-scale online education has been helped by an expanding adult student population that is technologically savvy. There is an expectation that 21st century adults will constantly improve their workplace skills at low cost and have more computational technology experience than previous generations.

The perception of MOOCs as revolutionary has shifted in the last year as education leaders now discuss their drawbacks in tertiary education. For instance, the automatic grading technology used in MOOCs was not created to support rigorous examination of large numbers of students. This therefore affects the accreditation possibilities of a MOOC. As with the early forms of any technology a degree of failure is inevitable; this allows users and creators to understand its collective uses and therefore improve the technology for specific contexts.

MOOCS in practice

The education industry has invested heavily in the development of online platforms that host MOOCs and so it is likely that online education possibilities continue. Two major players have emerged worldwide: EdX, which has affiliations with US university heavyweights such as Harvard, MIT and the University of California, Berkeley; and Coursera, which is used and supported by prestigious institutions such as Stanford and Brown Universities, in the USA and the University of London. Many other tertiary institutions and colleges around the world are associated with these two online delivery platforms.

Because there is usually minimal or no charge to enrol in a MOOC, companies such as EdX and Coursera need to recoup their investments through other sources. They might, for example, charge for course materials such as e-books. Or they may collect fees for helping to match employers with employees who have the skills they are looking for.

In 2013, Coursera was funded through US$85 million in venture capital and enrolled 5.2 million users. The contract between Coursera and participating universities includes a 'brainstorming' list of ways to generate revenue. These include certification fees and charges to introduce students to potential employers and recruiters (with student consent), as well as for tutoring and tuition.

Why have the world's universities embraced MOOCs so comprehensively? To begin with, online education can be highly cost-effective. Plus, it provides the opportunity to attract new students from under-serviced markets and new ways of doing business that fits a globally distributed student body. Increased competition in the global higher education market is highly likely and physical infrastructure, such as universities, is no longer essential for free online tertiary education. Therefore growth nations such as India, projected to require 1500 new educational institutions in the near future, are highly likely to embrace this form of learning.

MOOCs in the workplace

One dilemma about MOOCs has been how to practically acknowledge the time that students put into them and the information they gain. A link with a reputable university or college obviously confers trust, status and value on the information available online. But, it's not just the names of course backers that employers want to see.

EdX, which received US$30 million from MIT and Harvard and made online tertiary education courses available to 1.2 million users in 2012, provides certificates of achievement verified through personal identification. EdX is also currently testing new methods of certifying education by investigating the potential to provide businesses with tests to assess prospective employee knowledge.

LinkedIn – the professional social networking site that connects employers and employees – is also looking at ways to provide credit for MOOCs. It's partnering with education technology companies, including Coursera and EdX, to offer MOOC certifications for online classes. A new 'Direct-To-Profile Certifications' pilot program will allow users to display competed online courses on their LinkedIn profiles by clicking a link in an email from the course provider.

Australia's approach

Some of Australia's most prestigious universities have also begun to embrace MOOCs as a way of complementing existing traditional education programs. The University of Melbourne, for example, is incorporating Coursera MOOCs material into on-campus subjects. The Australian National University recently made free online courses available through EdX. And in 2013 University of NSW and the University of Western Australia announced plans to participate in MOOCs through Coursera.

MOOCS and other forms of online education are, however, certainly not seen as replacements for on-campus education in Australia, and there are several critical reasons why. Most significantly, MOOCs do not offer degree programs. Also, Australian universities rarely offer credit for overseas MOOCs courses and Australian students cannot receive income support for solely studying a MOOC. There's also the on-campus social and lifestyle experiences that MOOCs could never replace.

Inventing the future of education

MOOCs are being seen as an *indicator* of where the education sector is likely to head. For example, 'A thousand year old industry on the cusp of profound change' is the view of multinational financial services firm Ernst & Young [335].

So what is it about the online learning space that is so appealing? There are two key factors: control at the level of the individual learner and flexibility.

Online access to course content allows students to control lecture speed and format so that they can optimise their education by using their dominant mode of learning. And because all students can have access to the same level of background knowledge, they can tailor lectures and have improved engagement in tutorials, which maximises their opportunities for understanding.

This means that students can access and review the content of lectures in their own time by watching them from anywhere, whenever and however many times they want. And this increases the time available to debate and solve problems with peers and tutors in the classroom – skills that are highly sought after in the workplace. This flexibility is known as 'flipping the classroom'.

Low-cost online courses can make education available to a wider range of people. It can improve educational equality and allow access to learning for people with disabilities, on low incomes, and with limited free time. The system also allows universities to project their brands right around the world as well as identify their best students globally. MOOCs are not seen as a university replacement but as a way of improving the higher education and workforce skill sets. In fact, the highest levels of MOOC enrolments have been among students with prior tertiary education.

Future online tertiary education possibilities

So where to from here? MOOCs are likely to downsize and evolve from massive to private use, for delivery on a smaller scale as Small Private Online Courses (SPOCs), which combine online resources and technology with personal faculty-student engagement to provide in-classroom teaching to a significantly smaller number of students than MOOCs. Early research indicates that fostering a valuable classroom experience might improve higher education online courses.

Individually paced and personalised instruction is key to high-quality learning. MOOCs have shown that this type of information delivery is no longer limited to students with excellent face-to-face interaction with instructors.

Online education platforms allow unprecedented experimentation in learning and teaching on a large-scale. A truly vast amount of pedagogical data can be attained through online education. What helps or hinders learning can now be analysed on a global scale. And even more importantly, this can be fed directly back into the system to improve it. Currently, online education is promoting innovation in areas such as adaptive and personalised e-learning, teacher training and peer assessment.

Online tertiary education also provides huge opportunities to attract new students from under-serviced markets through branding of online courses. It opens up potential new revenue sources for educators; creates opportunities through global partnerships; and increases access to both student and academic talent.

Tertiary education's global marketplace

Increased competition for the global higher education market is inevitable. Because physical infrastructure is not essential for free online tertiary education, this form of education is likely to be embraced by future growth markets. It's predicted that India, for example – which is forecast to need 1500 new educational institutions in the near future – will have a large demand for this form of learning.

The opportunities for online education platforms are also likely to be high for China. The tertiary education participation rate in China tripled from 8% to 25.9% between 2000 and 2010. It's projected to double again in the next 10–15 years. There's enormous potential for Australia to embrace online tertiary education technology to support these growing markets.

Online education could also streamline and improve on-campus costs for Australian universities as well as representing an important new funding stream. This form of education enables providers to be innovative about the quality, length and cost of their offerings. It could be possible to offer shorter, cut-price degrees that are demonstrably equivalent (in terms of employability) to current degrees. Already in the USA, there is pressure on publicly funded universities to accept online credits. And although there are no expectations that MOOCs will *replace* on-campus degrees there is certainly a movement to see them acknowledged as part of the process. The American Council on Education, for example, is planning to evaluate MOOCs for college credit.

There are no similar plans as yet for Australia. But just as photocopiers allowed for the en masse replication of affordable learning resources, on-line delivery of information seems likely to become a part of mainstream of tertiary education.

Full working paper available at http://acola.org.au/index.php/new-technologies-contributing-reports

C.9. Tinkering with technology: examining past practices and imagined futures

Overview

- Tinkering is a hands-on creative approach to a problem.
- Viewed in a positive light, tinkering requires and generates an ability to adapt creatively and inventively to changing circumstances.
- Viewed in a negative light, tinkering is an unprofessional hack or quick fix.
- Tinkering reworks ideas around failure as part of the invention process. Failure does not mean the death or end of an idea but rather is part of the innovation process and can reveal new ways of thinking about a problem/ task/ solution/ idea.
- There has been a recent increase in global markets for products that value and celebrate their tinkered nature or tinkering potential, including mobile apps, 3D printers and software plug-ins.

Introduction

Tinkering, a practice that has been around since medieval times, historically involved the re-use and re-appropriation of scarce materials for the purposes of scavenging, adapting and fixing. It was associated with economic necessity, which for many imbued it with lower socio-economic pursuits, and poor quality temporary or non-professional results. Tinkering has acquired a new contemporary reputation: as a lynchpin for digital technological innovation. The increased availability of communication platforms and markets worldwide has enabled people to 'tinker' on independent projects, from making and selling apps to modifying open source code, creating new recipes or personalising their home computer or entertainment systems. Tinkering re-works conventional notions of consumers as passive receivers of goods to creative agents of technological change. The obstacles that lie between coming up with an idea, delivering on it and finding a market are shrinking, and with that, the demarcation between the so-called 'professional' device manufacturer and 'amateur' tinkerer.

Australia has a long recognised history of tinkering and inventive hands-on practices. Regardless of the empirical evidence of Australia's 'natural affinity' for tinkering, there is an opportunity to claim and cement this myth for Australia's technological future.

Tinkering and culture

Tinkering is a familiar term in Australian culture. Living and working in Australia has always required innovative thinking. The survival of farmers settling Australia in the early 19th century depended on their ability to repair their equipment, tasks that often required considerable skill. One example of tinkering from early pioneering days was the invention of the stump-jump plough by Ron Smith from Yorke Peninsula, South Australia. Stumps of the Mallee tree – a species of eucalyptus that frequently broke plough bolts, frustrated many farmers attempting to clear their land. The stump-jump plough literally jumped over stumps, allowing new land to be cultivated.

Tools and sheds were early on associated with tinkering in Australian culture, (see for example Mark Thomson's *Makers, Breakers and Shakers: Inside Australia's Most Resourceful Sheds*.) Writers like Thompson argue that sheds were sites where new technologies encountered domestic ecologies. Artefacts were moved from the house to the shed and given a new lease of life (or left in pieces to gather dirt until the right moment). Tinkering in the shed operates as a lens for looking at stuff anew and for imagining new applications.

Make-do and mend

Tinkering achieved new status during the Second World War when it became part of the British Make-Do and Mend movement. Men and women were encouraged to fix rather than replace household goods and clothing in order to avoid wasting scarce resources. The practice – which was often taken up with imagination and creativity – achieved a strong presence in Australia as a result of the nation's close ties with Britain. This sort of tinkering – in which jumpers were unpicked and re-knitted or decorative patches were used to cover worn garments – was a response to austerity and has gained renewed popularity in some sectors in recent years, again in response to economic necessity.

A good thing?

Tinkering has both positive and negative connotations. Among the former, tinkering is often seen as an activity linked to self-reliance, an aptitude for ingenious solutions to practical problems. It reveals a creative inquiring approach to the material world, and an ability to adapt and customise to suit changing conditions or circumstances.

Those who view tinkering in a negative light believe it involves low-level skills and cheap materials, rather than commensurate with high-tech, productive activities. Along these lines, tinkering occasionally features in common parlance as the practice of not quite getting to the core of a problem but rather just operating on the surface. For example unpopular laws for schools are dismissed as 'tinkering with education'.

Adopt and adapt

Technology does not have one meaning or use and is never static – the process of adopting technology is innovative. The concept of the active consumer recognises a shift from the passive receiver of goods to one that has agency, creativity and engagement in practices of inventive interpretation and resistance. It recognises that consuming involves the process of tinkering as a way of constructing meaning and regards 'users' as creative agents of technological change. Consumers can also be classified as tinkerers in the way they use technologies beyond the designer's expected application.

Types of tinkering that have now become popular include building and selling smartphone apps; fundraising for projects on crowd-funding sites such as Kickstarter; downloading step-by step instructions from websites to construct goods or modify software; tweaking recipes; and using 3D printers to make products. These assemblies of skills, practices and resources and access to peer-to-peer networking were previously only available to people embedded in large-scale centres of innovation.

Apps, for example, present opportunities for individuals to gain entry into commercial markets that were previously unobtainable because they were controlled by major technological companies or networks. It is estimated that today, owners of smartphones and tablets spend more than two hours a day on apps, a figure that has doubled over the past year and is expected to continue to rise at a steep rate for many years to come. One analyst argued that by 2017, mobile apps will be downloaded more than 268 billion times and will generate more than $77 billion in revenue.

Statistics indicate that Australians are among some of the top consumers of apps and one of the world's heaviest users of smartphones and tablets. Yet, although enthusiastic app downloaders, Australians are not major league app creators. Its share of app manufacture barely existed five years ago, but has shown promising signs of improvement having gone through an annual growth of 85% in the past five years to reach a revenue of $392 million in 2013–2014. Observers believe it is important that this trend continues; using apps costs money and making apps generates profits, as Google noted in its 2013 report, *Towards an Australian Innovation Generation*.

The maker movement

The global consultancy company Deloitte has pointed out: 'The emerging maker movement is the new mineral to mine and [is] the future industry in Australia.' Greater education directed towards entrepreneurship as an acceptable career path, and encouraging a 'fail fast' approach is critical to the maker mentality.

Maker Faires, which were created by *Make: magazine*, have become popular events around the world since their launch in the United States. Described by *Make:* as 'family-friendly festivals of invention and creativity', they are usually attended by thousands of individuals.

Another feature of the maker movement are Fab Labs, community 3D printing and fabrication workshops that support small businesses, schools and individuals by providing free or low cost access to equipment and expertise. Originally launched by Massachusetts Institute of Technology, there are now 200 Fab Labs located in 40 countries, and an increasing number of Fab Labs across Australia. It is free to join and open to students, inventors, hobbyists, small businesses, designers and artists and offers the use of technologies that include laser cutters and 3D printers.

Creators or consumers?

It is only a matter of time before Australia begins to feel the impact of the changing nature of people's desire to experiment with products. The question is: does the nation want to be one that creates technology or simply consumes it? A change in focus from the consumption of technology to the creation of technology will only help Australians compete in an increasingly connected world. Another report, *The Startup Economy: How to support tech startups and accelerate Australian innovation*, produced by Price Waterhouse Cooper, argues that the Australian technology start-up sector could contribute an extra $109 billion to the economy and 540,000 new jobs by 2033.

In order to realise this potential, a cultural change will be needed, one that includes 'greater education directed towards entrepreneurism as an acceptable career path' and addresses the fear of failures which 'dogs Australians more than people from other nations', as Ben Hurley points out in 'Aussie startups could earn $109b – if nourished, says Google', Financial Review, 23 April 2013. Greater emphasis on training students in the fields of digital technology and computer science – including mandatory computer science classes from kindergarten to Year 10 – could help provide the specific skills that are needed to generate entrepreneurial success.

Tinkering and gender

The concept of tinkering is widely regarded as predominantly masculine. Few heroic narratives of 'making-do' feature women's stories. This point is made by T. Klief and W. Faulkner in *'I'm no Athlete [but] I can Make This Thing Dance!" – Men's Pleasures in Technology [569]*. 'Boys are more likely than girls to be socialised into hands-on tinkering with mechanical devices.' Others also observe that making-do carries associations of colonial, white mythology. Questions therefore need to be asked about this stubborn practice of representation, a point stressed by S. Jackson in *Sacred Objects – Australian Design and National Celebrations [528]*. He says that the making-do 'myth' is colonial, white and deeply embedded in the Australian outback, and takes particular grievance that it is still a widely accepted and celebrated approach to Australian innovation and design. He considers it tired, out-of-date and questions why there are far fewer representations of innovative Australians as urban 'hi-tech people"'.

There are exceptions however. Images from the successful Maker Faires regularly showcase a range of makers and Fab Labs work hard to represent the diversity of users. There are also women's only hacker spaces and events.

Conclusion

There is compelling evidence that the way to teach people better STEM skills is to put it in context and let them play and tinker. Tinkering blurs conventional barriers between disciplines – such as art and science, theory and practice, work and play. Providing encouragement and support to Australian schools and other organisations to facilitate the development of tinkering, including fostering the attitude that it is ok to try and fail, and a refusal to accept the status quo as acceptable, could pay huge long-term dividends for Australia. An Australia where every citizen is willing to tinker and improve the way things are done will be an Australia that continues to get better.

Tinkering promises a way to respond to changing conditions, the tyranny of distance, complexity of supply chains, rising costs and growth of new global digital technology markets – all factors that relate well to the Australian context. Moreover, tinkering is a familiar term in Australian culture; recognised as being something that Australians do naturally and well. Regardless of the empirical evidence of Australia's 'natural affinity' for tinkering, there is an opportunity to claim and cement this myth for Australia's technological future.

However, there are barriers that need to be addressed. There is an assumption that tinkering is something that comes naturally. However, people can be taught to tinker. Tinkering is also often associated with poor or low level skillsets and there is a lack of encouragement for risky entrepreneurial behaviour in Australia. Individuals skilled in topics such as digital technology and software coding are also in short supply. In addition, tinkering is all too often seen as an enterprise more suited to particular types of people – a tendency that unfairly skews the take-up of tinkering throughout the population.

A number of actions are suggested. In-depth studies of tinkering and perceptions of failure in Australia would also be useful. It would also be worthy to explore ways to teach tinkering both as a theory and a practice.

Full working paper available at http://acola.org.au/index.php/new-technologies-contributing-reports

Appendix 3: Evidence-gathering activities

Workshops and consultations

SAF05 held four workshops during the project, on four different topics:

1. Australians imagining technology: fears, hopes, anxieties, dreams (6 June 2014 in Sydney)
2. Technology prediction and planning (23 July 2014 in Sydney)
3. Regulating technology and the technology of regulation (30 July 2014 in Canberra)
4. Impact of science and technology in industry (14 August 2014 in Sydney and Melbourne).

Summary notes from each workshop can be found at http://technologyforaustralia.org/workshops-2014/

The SAF05 Expert Working Group and project team wish to thank the following people for their participation at workshops and/or contribution to the project:

Dr Greg Adamson, Chair of IEEE 2014 Conference on Norbert Wiener in the 21st Century
Dr Mamoun Alazab, ANU Cybercrime Observatory
Mr James Alexander, Incubate
Associate Prof Margaret Allman-Farinelli, University of Sydney
Mr Joe Amoia, Sphere3 Consulting
Ms Peta Ashworth, CSIRO
Prof Marian Baird, University of Sydney Business School
Dr Thomas Barlow, Barlow Advisory
Dr John Bell, ACIL ALLEN Consulting
Dr Ron Ben-David, Essential Services Commission
Dr Lyria Bennett-Moses, University of New South Wales
Mr Charles Britton, Australian Communications and Media Authority
Dr Michael Bruenig, CSIRO Digital Productivity and Services Flagship
Prof Brad Buckley, University of Sydney
Associate Prof Jean Burgess, Queensland University of Technology
Dr Martin Callinan, Australian Academy of Science
Ms Heather Catchpole, Refraction Media
Prof Nick Cerneaz, The Warren Centre for Advanced Engineering Ltd
Prof Janet Chan, University of New South Wales
Prof Tim Coltman, University of Wollongong
Associate Professor John Conomos, University of Sydney
Mr Michael Cosgrave, Australian Competition and Consumer Commission
Professor Edmund J. Crampin, Systems Biology Laboratory and University of Melbourne
Mr Alistair Davidson, Australian Bureau of Agricultural and Resource Economics and Sciences
Ms Kate Delaney, Delaney Foresight Associates Pty Ltd
Dr Stephen Doherty, University of New South Wales
Mr Richard Eckersley, Australia21
Dr Dean Economou, NICTA
Mr Kerim El Gabaili, OnePoint
Dr Kate Fairley-Grenot, Chair of Agriculture Productivity Working Group of ATSE
Dr Bob Frater, ResMed
Mr Brendan Fitzgerald, Infoxchange
Emeritus Prof Arie Freiberg, Monash University

Dr Jenny Gordon, Productivity Commission
Prof R. Quentin Grafton, Australian National University
Mr Jordan Green, Melbourne Angels/ Australian Association of Angel Investors
Prof Peter Grabosky, REGNET Australian National University
Dr Michael Green, Trade, Manufacturing, Aviation and Employment Division, Victoria
Ms Michelle Groves, Australian Energy Regulator
Dr Nitin Gupta, SAF01 project, Academy of the Social Sciences in Australia
Adjunct Prof Phillip Hall (PH), University of Western Australia
Dr Mark Harrison, SMART University of Wollongong
Dr Carrie Hillyard, ATSE Queensland Division Committee
Dr Justine Humphry, University of Sydney
Dr Leila Iranmanesh, University of New South Wales
Mr Jeevan Joshi, Learning Café
Dr Michael Kearnes, University of New South Wales
Dr Paul Kelly, One Ventures Pty Ltd
Mr Peter Laver, Australian Academy of Technological Sciences and Engineering
Prof Andre Luiten, Institute for Photonics and Advanced Sensing
Prof Deborah Lupton, University of Canberra
Emeritus Prof Roy MacLeod, University of Sydney
Dr John Mattick, Garvan Institute of Medical Research
Mr Daniel McCracken-Hewson, Office of the Hon Bruce Billson MP
Prof Donald McNeill, University of Western Sydney
Associate Prof Katina Michael, University of Wollongong
Mr Daniel Musson, Australian Institute of Management
Mr Buzz Palmer, Small Technologies Cluster Australia
Mr Jim Patrick, Cochlear Ltd
Ms Zoe Piper, Australian Chamber of Commerce and Industry
Dr Leanna Read, BR-Angels Pty Ltd
Mr Peter Robinson, QMI Solutions
Mr John Smartt, SmartSynthesis
Dr Gavin Smith, Australian National University
Dr John Soderbaum, ACIL ALLEN Consulting
Mr David Spriggs, Infoxchange
Mr Andrew Stead, New Ventures NICTA
Associate Prof Melanie Swalwell, Flinders University
Dr Alex Taylor, Microsoft Research, Cambridge
Dr Emmeline Taylor, Australian National University
Dr Kieran Tranter, Griffith University
Mr Alex Varley, Media Access Australia

Additional workshops

The SAF05 project sponsored and participated in two additional workshops:

- Institute of Electrical and Electronics Engineers (IEEE) Society on Social Implications of Technology (SSIT) Australia/SAF05 workshop (3 August 2013 in Melbourne)
- The Eighth Workshop on the Social Implications of National Security: Remotely Piloted Airborne Vehicles and Related Technologies (29-30 September, 2014 in Melbourne)

Online survey

The SAF05 project ran an online survey in September 2013, asking participants to propose technologies important for Australia and the enablers and barriers for adoption and diffusion. Over 110 responses were received. We thank all participants for their time and input.

Acronyms

AI	artificial intelligence
ATM	automatic teller machine
CT	computerised tomography
DDT	dichlorodiphenyltrichloroethane [an insecticide]
EFTPOS	electronic funds transfer at point of sale
GDP	gross domestic product
GM	genetically modified [crop/s]
GPS	global positioning system
ICT	information and communications technology
IP	intellectual property
IT	information technology
LED	light-emitting diode/s
MOOC	massive open online course
NBN	national broadband network
OECD	Organisation for Economic Co-operation and Development
OH&S	Occupational [or workplace] health and safety
STEM	science, technology, engineering and mathematics
URL	uniform resource locator [internet address]

Acknowledgments

On behalf of myself and my co-chair Rob Evans, I acknowledge and thank:

The expert working group for their advice, arguments, written inputs, patience and careful (and repeated!) reviewing.

NICTA for their in-kind support over the past two years. In particular NICTA's Canberra Research Laboratory for providing the team with office space, meeting facilities, computer infrastructure and administration and IT support.

The Australian National University and University of Melbourne for supporting the project through the time of Rob and myself, travel costs, and library resources.

Dr Bernadette Hince for her attention to detail and love of words.

Dr Lyria Bennett-Moses for her outstandingly cogent discussions and detailed written feedback on parts of the report.

Dr Katrina Jungnickel for her initial contributions as a project team member, and subsequent continued interest and input.

Professor Edmund Crampin for his contributions to several expert working group meetings.

Dr Martin Callinan and Mr Ben Patterson of the Australian Academy of Science for their support.

Dr Ryan Herbert and Dr Simon Prasad of the Office of the Chief Scientist for their guidance and advice.

Ms Rebecca Skinner and Dr Renée Dutton of ACOLA for their assistance and support.

Ms Heather Catchpole and her team at Refraction Media for the initial distillation of the case studies from the working papers.

Many people willing to listen to aspects of the project and offer their valuable advice, including Merritt Roe Smith, Rosalind Williams (for her encouragement to not view technology from too narrow a perspective), Rodney Brooks, Michael Barber and other members of the Project Steering Committee, Katina Michael, Jenny Gordon, Ralf Herbrich, Greg Adamson, Simon Kaplan, John Bell, Glenn Withers, Tegan Donald, Phil Robertson, Michelle Simmons and Lindell Bromham.

The anonymous reviewers and ACOLA council members who provided detailed comments on the entire report. Robin Batterham declared himself as a reviewer and we thank him for his insightful comments as well as for his foreword to the report.

Our families for putting up with the work hours and distraction this project induced.

I *especially* want to thank and acknowledge the awesome project team for their alacrity, assiduity, ardour, astuteness, audacity, autonomy and their ability to deal with ambiguity, complexity, dissonance and diversity. Their efforts over two years have been outstanding and I have greatly enjoyed working with them:

Ms Dana Sanchez (who also served as the supremely efficient project manager)

Dr Chelle Nic Raghnaill

Dr Kirsty Douglas

Robert Williamson, co-chair

Project team

Dr Chelle Nic Raghnaill received a PhD in neuroscience at University College Dublin, followed by post-doctoral fellowships in nanotechnology. She has published in the fields of neuroscience, pharmacology, nanotechnology and regulatory reform. Past experience includes leading international collaborations to improve understanding on the human health risks of nanomaterials and co-authorship of the first regulatory considerations report to inform and stimulate discussion about emerging nanotechnology. Currently, she is project officer for the Environment Business Team at NICTA.

Dr Kirsty Douglas is an environmental historian and historian of science, with a background in geology, environmental regulation and science administration. Her current interest in the transformative capacity of technology stems both from the study of the history of science and from public sector experience in research data infrastructure and the information domain.

Dana Sanchez studied at the Australian National University. She has since worked in the university and research sectors in the fields of life sciences and ICT. In her current position at NICTA she works in the areas of research management and innovation.

Expert working group

Professor Rob Evans FAA, FTSE (Co-Chair)

Professor Rob Evans worked as an engineering officer with the Royal Australian Air Force and completed a PhD at the University of Newcastle, followed by postdoctoral positions at MIT and Cambridge University. His academic roles include Head of the Electrical Engineering Department at both the University of Newcastle and the University of Melbourne, and Executive Dean of Engineering at the University of Melbourne. He has served in leadership roles in a number of research centres including the ARC Centre on Industrial Control Systems, the Cooperative Centre for Sensor Signal and Information Processing, the DSTO Centre for Networked Decision Systems, the Victoria Research Laboratory of National ICT Australia, and the Defence Science Institute.

Over the past 40 years Professor Evans has worked extensively with industry in Australia and overseas especially in the areas of industrial control and electronics and civil and military radar systems. He is a Fellow of the Australian Academy of Science, Academy of Technological Sciences and Engineering, Institution of Electrical and Electronic Engineers, USA, and Institution of Engineers Australia.

Professor Robert C Williamson FAA (Co-Chair)

Professor Robert (Bob) Williamson's interest in technology started at age eight tinkering with electronics, and in the 1970s operated a ham radio station (call-sign VK4ARW). He studied electrical engineering at QUT, obtained a Master of Engineering Science and PhD (in electrical Engineering) from the University of Queensland and since 1990 has been at the Australian National University, currently in the Research School of Computer Science.

He was instrumental in the creation of NICTA, and served as foundation Canberra laboratory director, and then later as scientific director. He currently leads NICTA's machine learning research group and his personal technical research is focussed on theoretical aspects of machine learning. His current project aims to build a problem-oriented foundation for all of machine learning by focussing on the end-problem being solved, rather than the technique used. He is a fellow of the Australian Academy of Science.

Dr Genevieve Bell

Dr Genevieve Bell is a vice president and Intel Fellow in the Corporate Strategy Office at Intel Corporation. Bell joined Intel in 1998. She has been granted a number of patents for consumer electronics innovations throughout her career, with additional patents in the user experience space pending, and is the author of numerous journal papers and articles. She was named an Intel Fellow in 2008.

Dr Bell has been featured in publications such as *Wired*, *Forbes*, *The Atlantic*, *Fast Company*, the *Wall Street Journal* and the *New York Times*. Her industry recognition includes being listed among the 100 most creative people in business by Fast Company in 2010, induction in the Women in Technology International Hall of Fame in 2012, and being honored as the 2013 Woman of Vision for Leadership by the Anita Borg Institute. Bell's book *Divining a digital future: mess and mythology in ubiquitous computing*, written in collaboration with Paul Dourish, was published by MIT Press in 2011. She holds a combined bachelor's and master's degree in anthropology from Bryn Mawr College and a Master's degree and PhD in cultural anthropology from Stanford University, where she was a lecturer in the anthropology department from 1996 to 1998.

Professor Rod Broadhurst

Professor Broadhurst is Professor of Criminology, Department of Sociology, Research School of Social Sciences, Australian National University. He was founding fellow of the Hong Kong Centre for Criminology and foundation editor of the *Asian Journal of Criminology*. His 40-year career as a practitioner and researcher has included work in prisons, research in remote area public health, and research into homicide. He has led research on crime victims in Cambodia and China and has contributed widely to the field of criminology in Australia and Asia. He directs the ANU Cybercrime Observatory.

Recent books include *Business and the risk of crime in China* (ANU Press 2011), *Policing in context* (Oxford University Press 2009) and *Violence and the civilizing process in Cambodia* (Cambridge University Press 2015).

Professor Gerard Goggin

Gerard Goggin is Professor of Media and Communication and ARC Future Fellow at the University of Sydney. He has a longstanding research interest in technology, society and culture. He has published *Digital disability* (2003), *Virtual nation: the internet in Australia* (2004), *Cell phone culture* (2006), *Global mobile media* (2010), *New technologies and the media* (2011), the *Routledge companion to mobile media* (2014), and *Locative media* (2015). Gerard is involved in public policy and technology in Australia, especially in relation to consumer, public interest, and humanities issues.

Professor Ron Johnston FTSE, FRSN

Professor Ron Johnston is Executive Director of the Australian Centre for Innovation and a Professor in the Faculty of Engineering & IT at the University of Sydney. He was educated as a scientist in Australia, UK and the US. He has devoted most of his career to developing a better understanding and application of the ways in which science and technology contribute to economic and social development, the possibilities for managing research and technology more effectively, and insights into the processes and culture of innovation.

Dr Michael Keating AC, FASSA, FIPAA

Dr Michael Keating was head of three Australian Government departments from 1983 to 1996: the Departments of Employment and Industrial Relations, Finance, and Prime Minister & Cabinet. Since then he has held positions at the Australian National University and Griffith University. He has been a member of various private and government boards, and continues to work as a consultant to major companies and governments on corporate and government strategy and policy development.

Dr Keating has published various economic and employment related articles and co-authored a book on Australian economic policy. He has also published extensively in Australia and overseas on the capacity of our system of governance and public sector management reform. His book *Who rules? How government retains control of a privatised economy* (Federation Press, 2004) discusses the relationship between markets, government and society

Professor Stephen King FASSA

Professor Stephen King is Professor of Economics at Monash University and Chairman of the Economic Regulation Authority of WA. Before joining Monash University, he was a Member of the Australian Competition and Consumer Commission, where he chaired the Mergers Review Committee.

Professor King's main areas of expertise are competition economics, regulation and industrial organisation. He received the University Medal from the Australian National University for his undergraduate studies in economics. He has a Masters in Economics from Monash University and a PhD from Harvard University, and is a Fellow of the Academy of Social Sciences in Australia.

Emeritus Professor John O'Callaghan FTSE

John O'Callaghan is a consultant on information and communications technologies with application to all areas of science and engineering.

His previous positions include those of Interim Director, Victorian Life Sciences Computation Initiative; Executive Director, Australian Partnership for Advanced Computing; Chief Executive Officer, CRC for Advanced Computational Systems; and Chief, CSIRO Division of Information Technology.

He is an Emeritus Professor of the Australian National University, a Fellow of the Australian Academy of Technological Sciences and Engineering, and a recipient of the Pearcey Medal for contributions to Australian ICT.